Studies on Communication Quality Improvement Technology in Media Access Control Scheme for Wireless Local Area Network Systems

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Abstract

This dissertation presented research results regarding techniques of improvement on communication quality in Media Access Control (MAC) protocol for Wireless Local Area Network (WLAN) systems. A wide variety of devices including mobile devices such as smartphones, tablet PCs, mobile routers, gaming machines, and sensor devices utilizes WLAN systems in these days and applications used in those devices have been diversified. Furthermore, the utilization of WLAN systems will also increase rapidly because of traffic offloading from mobile communication systems. Therefore, the demands for the communication quality improvement and high speed transmission of WLAN system are increasing. However, these demands to WLAN systems resulted in the increase of congested situations with many WLAN stations, i.e., wireless dense environments. In the wireless dense environments, shortage of bandwidth resource is caused and sufficient communication quality is not ensured by mechanism of contention based MAC protocol of WLAN systems. WLAN systems employ the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) as their MAC protocol. The CSMA/CA shares the same wireless medium for communications and each station segregates its transmission timing by random access manner. In the CSMA, Stations (STAs) autonomously decide the transmission timing and this mechanism causes simultaneous transmission among multiple STAs. This simultaneous transmission causes collisions of the transmitted signals, which means each signal is interfered with other signals and the receiver may not be able to detect the desired signal correctly. In wireless dense environments, the probability that two or more STAs transmit signals simultaneously increases and that results in generating a large number of collisions. Moreover, the mechanism of the CSMA/CA generates other issues. The CSMA/CA is designed in such a way that the priority for transmission from all STAs is impartial. In other words, no user level priority control is constructed in the existing WLAN systems. Therefore, establishing Quality of Service (QoS) control architecture for each user level priority control is required to enhance communication quality. Furthermore, WLAN systems suffer from mutual system interference caused by other wireless systems because WLAN systems do not provide any mechanism for protection against the interference. Sophistication of WLAN systems have been progressed in the IEEE 802.11 standard association. A lot of the standards regarding WLAN systems were published to improve transmission rates and to enhance various function for convenience. However, the fundamental MAC protocol of WLAN systems is nearly unchanged due to maintaining interoperability. This conventional design of MAC protocol of WLAN systems cannot cope with issues raised in the wireless dense environments.

In this study, in order to resolve these issues, the following three techniques were established. First, a simple and adaptive frame collision control scheme that can mitigate severity of contention for obtaining channel access was proposed in order to reduce heavy collisions between STAs that cause co-channel interference. Second, a pseudo-centralized control technique that enables control of flexible bandwidth allocation to each specific STA was proposed in order to establish a control mechanism of user level

priority for WLAN systems. Last, a scheduling technique that controls timing of transmission for WLAN systems was proposed in order to avoid mutual system interference between WLAN and other wireless systems. The following summarizes the organization of this dissertation and the results obtained through this research.

In Chapter 1, the background, the historical progress of WLAN systems, the technical challenges and the purpose of dissertation were described.

In Chapter 2, the mechanism of existing MAC protocols of the IEEE 802.11 WLAN systems was explained and the importance of MAC layer approach was mentioned.

In Chapter 3, a simple scheme that decreases the number of frame collisions for WLAN systems was proposed. After a successful transmission, the proposed scheme refrains from transmission during certain time. This mechanism improves the system performance by reducing the number of competing STAs. The results of the computer simulations showed that the proposed scheme achieves up to 40% higher system throughput compared to the case in which the proposed scheme is not introduced.

In Chapter 4, a flexible pseudo-centralized control scheme by using two kinds of fixed back-off value for back-off time was proposed. Though the CSMA/CA decides back-off value by random within the Contention Window (CW) range, the proposed scheme defines and adopts two kinds of fixed back-off value. This mechanism enables to control the user level priority and to improve the system performance. The results of computer simulations showed that the proposed scheme can achieve up to over 300% higher user throughput, compared to the case in which the proposed scheme is not introduced under the coexistence environment with the conventional STAs. In addition, all the proposed STAs achieved 70% higher throughput than the conventional STAs under a non-coexistence environment.

In Chapter 5, an interference avoidance technique that allows wireless device with similar frequency bands to be operated adjacent to each other for compact wireless mobile routers was proposed. In the wireless mobile router, mutual system interference is generated because the space between each device is very close and the frequency using each system is adjacent. To suppress this interference, the proposed scheme synchronizes the transmission and the reception timing of WLAN and the other wireless system using the IEEE802.11 Power Save Multi-Poll (PSMP). Computer simulations were conducted to show that the proposed scheme outperforms the conventional schemes. The proposed scheme succeeded in obtaining over 2000% higher throughput compared with the case in which the proposed scheme is not introduced.

In Chapter 6, the conclusions of this dissertation was mentioned.

The above research results showed significant enhancement of the performance of WLAN systems by introducing practical MAC schemes. The results should contribute to overcome ongoing and forthcoming difficulties in wireless dense environments.

Table of Contents

List of Parameters

Symbol	Unit	Description
a	-	Normalized propagation delay time.
a_e	byte	Payload of the Ethernet frame that doesn't come up to 1500 bytes.
a_e'	byte	Payload of the Ethernet frame that doesn't come up to 1500 bytes (after scheduling).
B_C	-	Cyclic back-off value.
B_I	-	Initial back-off value.
B_r	-	Total number of candidates for the back-off value of DCF STAs that avoid collisions
c	-	Number of collisions
C_{ex}	bit/s	Difference of traffic.
C_w	bit/s	Amount of traffic sent by WLAN AP.
CW	-	Number of contention window.
C_w'	bit/s	Amount of traffic sent by WLAN AP (after scheduling).
CW_{max}	-	Maximum number of contention window.
CW_{min}	-	Minimum number of contention window.
C_x	bit/s	Amount of traffic received at WiMAX MS.
C_x'	bit/s	Amount of traffic received at WiMAX MS (after scheduling).
e	-	Coefficient of proportion of data payload in DL Burst.
F	bit/s	Observed throughput.
G	bit/s	Offered traffic.
g	-	Arbitrarily group number.
G_x	bit/s	Amount of traffic from WiMAX MS.
i	-	Arbitrary number.
I_{init}	bit	Initial difference of estimated payload size.
J	-	Number of subcarriers allocated to wireless mobile router.
l	s	Length of OFDM symbol.
L	-	Number of subcarriers allocated to wireless mobile router.
L_{max}	-	Number of all OFDM symbols in DL Burst.
m	-	Modulation bit number.
n	-	STA number.
N	-	Number of STAs.
N_c	-	Number of conventional STAs.
n_p	-	Individual STA number for proposed STA.
N_p	-	Number of proposed STAs.
n_{ret}	-	Number of retransmissions.
n_u	-	Quotient to divide G_x by 1500 bytes.
n_w	-	Number of WLAN packets that can be transmitted in WLAN Downlink Phase.
n_w'	-	Number of WLAN packets that can be transmitted in WLAN Downlink Phase (after scheduling).

Symbol	Unit	Description
p	byte	Surplus to divide G_x by 1500 bytes.
P_n	s	Length of Post-IFS of the STA whose number is n.
R_{fxd}	bit/s	Specified transmission rate.
R_i	bit/s	Transmission rate of the STA whose number is i.
s	-	Number of all subcarriers of WiMAX DL Burst.
S	-	Normalized throughput.
S_{fxd}	bit	Specified payload size.
S_i	bit	Payload size of the STA whose number is i.
T	s	Time for the length of a data frame.
t_1	s	Extended WLAN Downlink Phase (after downlink scheduling).
$t_1{}'$	s	Final extended WLAN Downlink Phase (after uplink scheduling).
t_2	s	The minimum length of WLAN Uplink Phase (after uplink scheduling).
$T_{ACK,\ n}$	s	Duration that needed for an ACK frame exchange of the STA whose number is n.
$T_{Boff,\ n}$	s	Duration that needed for back-off time of the STA whose number is n.
$T_{DATA,\ n}$	s	Duration that needed for a data frame exchange of the STA whose number is n.
t_{DP}	s	WLAN Downlink Phase (before scheduling).
T_{fxd}	s	Specified duration that needed for a whole frame exchange.
T_{IFS}	s	Duration of IFS.
T_n	s	Duration that needed for a whole frame exchange.
T_{PDU}	s	Duration of data frame.
T_{PSMP}	s	Duration of PSMP frame.
T_{SIFS}	s	Duration of SIFS.
t_{UP}	s	WLAN Uplink Phase (before scheduling).
u	-	Number of all subcarriers of WiMAX UL Burst.
x	-	Number of iterations.
x_q	-	Granularity of U-QoS class.
y	-	Modulation bit number.
α	-	Coefficient step-size for Post-IFS estimation.
α_q	-	Ratio of proposed STAs to N.
β	-	Arbitrary number.
λ	-	Average sporadic rate of a data frame per second.

List of Figures

List of Tables

Chapter 1

Introduction

1. Introduction

1.1. Background

A Local Area Network (LAN) is a computer network that interconnects computers within a limited area using network media. Wireless LAN (WLAN) is a form of LAN and its network medium is space. WLAN systems were designed as alternative for wired LAN systems in the beginning as depicted in Fig. 1.1. However, WLAN systems have made amazing strides over the last decade and style of utilization has been changing. Terminals that use WLAN systems were almost personal computer (PC) in the earliest years, however, nowadays many mobile devices such as smartphones, tablet PCs, mobile routers, gaming machines, and sensor devices, utilize WLAN systems. The prediction concerning volume of shipments of mobile devices with WLAN interface [1.1] is shown in Fig. 1.2 According to the figure, the number of shipment of mobile devices with WLAN interface will reach approximately 55 million in 2016. These mobile devices are utilized at any place and applications that are used through these mobile devices are various. Therefore, there is a compelling need for enhancement of communication quality of WLAN systems that fulfills the demand of various applications from a lot of users.

On the other hand, traffic of mobile communication systems such as Long Term Evolution (LTE) or LTE-Advanced is also growing rapidly. Fig. 1.3 shows average monthly traffic of mobile communication systems [1.2]. The average monthly traffic increases by the twice every year approximately from 2010 according to the figure. Moreover, according to a forecast from Ref. [1.3], the traffic load of mobile communication systems will grow about 10 Exabyte per month in 2016. This rapid growth of traffic load leads to a bottleneck in the mobile communication systems. In order to cope with this issue, traffic offloading from mobile communication systems to WLAN systems is attractive solution. WLAN systems can cover a portion of heavy traffic of mobile communication systems because many mobile devices such as smartphone equip both interface of WLAN and mobile communication systems. Therefore, the utilization of WLAN systems will also increase rapidly because of traffic offloading from mobile communication systems.

This increase of utilization of WLAN systems has made change in style of utilization from initial design. WLAN systems are widely used in home, in office as well as many public areas including outdoors in recent days. WLAN systems became no longer “local area” network but important access network by this change. However, this sophistication of WLAN systems resulted in the increase of congested situations with many WLAN stations (STAs). Hereafter, this congested situation is referred as a wireless dense environment. Although improvement of function and speeding up of transmission rate of WLAN systems are in progress, the fundamental media access control (MAC) protocol of WLAN systems is nearly unchanged. This conventional design of MAC protocol of WLAN systems cannot solve issues raised in wireless dense environment. Therefore, this dissertation aims at improvement of the MAC protocol in order to solve issues that accompany the sophistication and the change of utilization in WLAN systems.

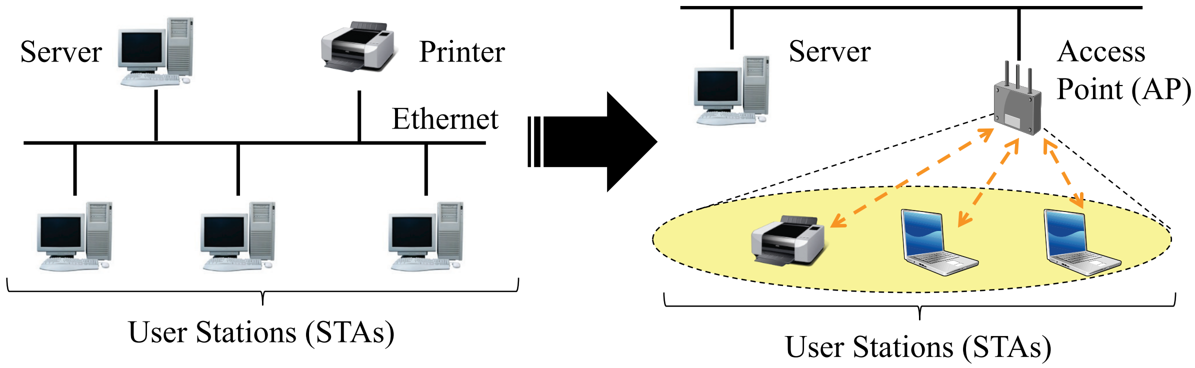


Fig. 1.1 Example of wireless local area network system.

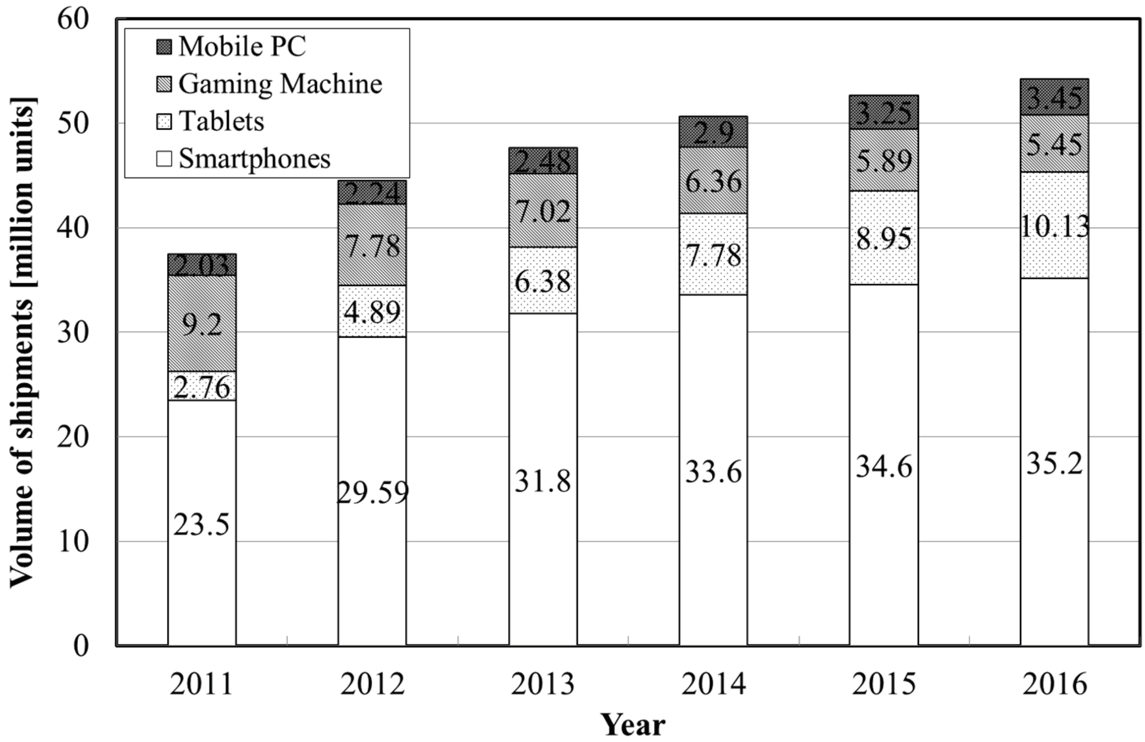


Fig. 1.2 Prediction of the number of shipment of mobile devices with WLAN interfaces.

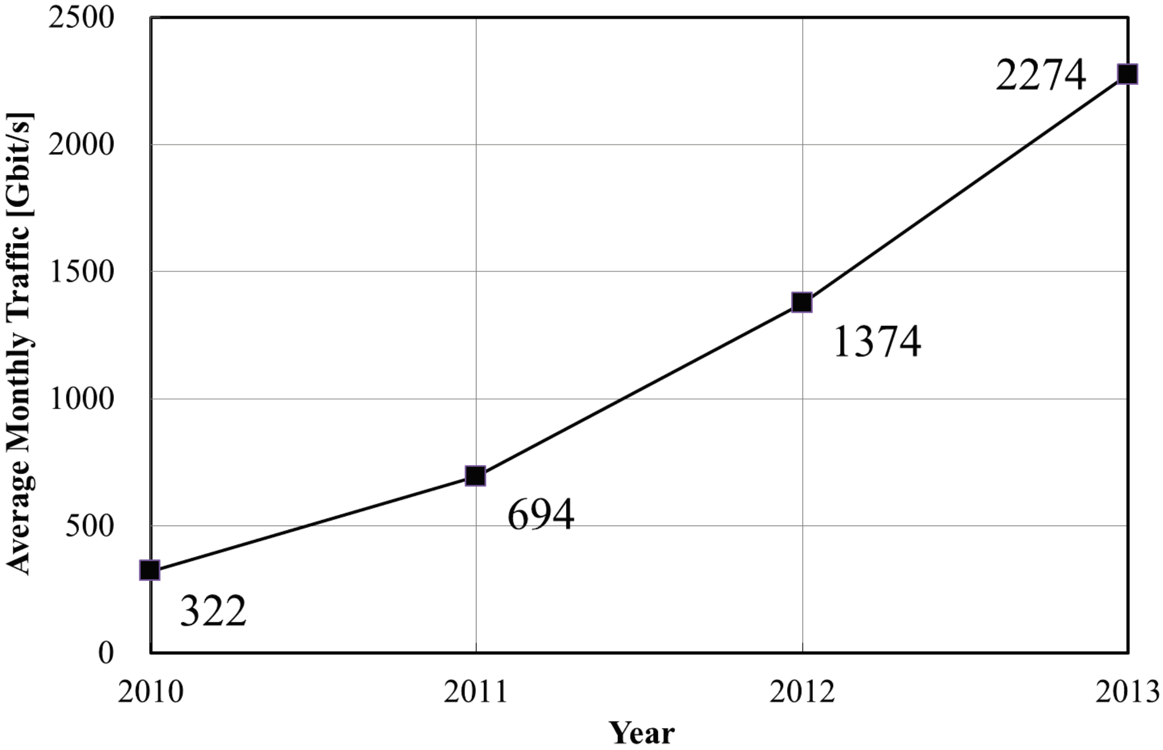


Fig. 1.3 Average monthly traffic of mobile communication systems.

1.2. Historical Perspective of WLAN

WLAN is originated from wireless system called ALOHA system [1.4][1.5]. This was the original wireless data exchange system using Time Sharing System (TSS). According to Ref. [1.6], development of the ALOHA system was begun in 1968 at the University of Hawaii for one of the early computer networking designs by N. Abramson and others, including F. Kuo, N. Gaarder and N. Weldon. Each Hawaiian island is distant from other islands and laying wired cable connecting these islands involves enormous cost. Therefore, goal of this system was to use low-cost commercial radio equipment to connect users with a central TSS on the main Oahu campus. In ALOHA system, a STA sends a short acknowledgement (ACK) frame when the STA receives a data frame correctly from the other side because each STA share its communication medium. This is the greatest feature of ALOHA system. Transmission failures due to frame collisions are generated because any STAs send a data frame when they want to do so. Each STA detects this transmission failure by the existence of the ACK frame. If the STA detects its transmission failure, the STA retransmit the data frame after waiting a randomly selected time interval. Although ALOHA systems had constructed feasible wireless network connecting Hawaiian islands, it had only transmission rate of 9.6 kbit/s. The system performance of ALOHA system is degraded because there is no consideration about frame collisions in the system. Therefore, N. Abramson and L. Kleinrock proposed Slotted ALOHA [1.7], which introduced discrete timeslots and increased the maximum performance. Thanks to this discrete timeslots, collisions occur only at the beginning of a timeslot and this reduces whole collisions. These ALOHA systems became an ancestor of all shared media networks.

In 1973, wired LAN system called Ethernet was developed by Xerox. It was inspired by ALOHA system by R. Metcalfe and had 2.94 Mbit/s transmission rate [1.8]. In 1980, the Institute of Electrical and Electronics Engineers, Inc. (IEEE) Computer Society established the “Local Network Standards Committee (LNSC)”, Project 802 (the IEEE 802 committee) [1.9]. The IEEE 802 committee aims to standardize specifications for physical media and media access control (MAC) protocols. In 1983, the IEEE 802 committee published the IEEE 802.3 standard that based on the Carrier Sense Multiple Access with Collision Detection (CSMA/CD). The CSMA/CD was developed based on ALOHA systems as the protocol for wired networks. The CSMA is based on the principle “listen before talk”, which means that a STA checks if the medium for transmission is in use or not before starting any transmission. Transmission rate of 10 Mbit/s over Ethernet using The CSMA/CD was realized by the IEEE 802.3 standard [1.10]. The concept of the CSMA/CD for Ethernet was applied to later wireless networks.

In 1990, the IEEE 802.11 Working Group (WG) was established to standardize specifications for WLAN systems. This activity yielded the first standard of WLAN that was published in 1997 as the IEEE 802.11-1997 [1.11]. According to Ref. [1.12], it was based on the regulation of the Industrial, Scientific and Medical (ISM) band for unlicensed use that released by the U.S. Federal Communications Commission in 1985. The IEEE 802.11 standard employed the Carrier Sense Multiple Access with Collision Avoidance

(CSMA/CA) as its MAC protocol. The CSMA/CA was designed for wireless networks and its protocol principle was based on the CSMA/CD. Maximum transmission rate of this standard was two Mbit/s with Direct-Sequence Spread Spectrum (DSSS) modulation or Frequency-Hopping Spread Spectrum (FHSS) modulation.

Two years after publishing of the first standard, in 1999, the IEEE 802.11 WG standardized two new standards with higher transmission rate. That is, the IEEE 802.11a and the IEEE 802.11b. The IEEE 802.11a operates in the 5 GHz band with a maximum data rate of 54 Mbit/s. The IEEE 802.11a employed Orthogonal Frequency-Division Multiplexing (OFDM) technique in order to enhance transmission rate. Although the IEEE 802.11a was published in 1999, commercial WLAN products that comply with the IEEE 802.11a was emerged in 2001. On the other hand, the IEEE 802.11b was designed so that STAs complying with the IEEE 802.11 standard can communicate with STAs that follow the IEEE 802.11b standard. In other words, backward compatibility for the conventional IEEE 802.11 standard was ensured on the IEEE 802.11b. Therefore, the IEEE 802.11b employed DSSS modulation and operates in the 2.4 GHz band with a maximum data rate of 11 Mbit/s. Furthermore, several companies formed a global non-profit association called Wi-Fi Alliance [1.13] with the goal of driving the interoperability for WLAN products among different vendors in 1999. Thanks to great deal of efforts by the IEEE 802.11 WG and the Wi-Fi Alliance, WLAN products with the IEEE 802.11 standards are rapidly being popular and prevailed. The Wi-Fi certification logo shown in Fig. 1.4 is given to a WLAN product that certified by Wi-Fi alliance. WLAN products which have the logo can interconnect each other regardless of the difference between product vendors. Therefore, the name of Wi-Fi become very popular and many people recognize Wi-Fi as WLAN systems itself.

After publishing of the IEEE 802.11a and b, the trends in the direction of the IEEE 802.11 standard are to upgrade transmission rate and to enhance function features. The list of the IEEE 802.11 standards at present is shown in Table 1.1. Note that this list contains the standards under development. As important factor in these standards, backward compatibility is mentioned. Therefore, how the STAs with new feature of WLAN can coexist with the conventional legacy STAs is very important factor for the research of WLAN systems. Moreover, the newly defined standards are mainly using 2.4 GHz and 5GHz bandwidth, however some of them aim at using other frequency bands including TV whitespace like the IEEE 802.11af [1.14].

The IEEE 802.11 standards continue remarkable development and realize much higher transmission rate with maintaining backward compatibility. The standard progress of WLAN is illustrated in Fig. 1.5. The IEEE 802.11n [1.15] was published in 2009 that operates at a maximum transmission rate from 54 Mbit/s to 600 Mbit/s in both 2.4 GHz and 5 GHz band. The IEEE 802.11n introduced Multiple-Input and Multiple-Output (MIMO) technique and this enabled significant improvement of transmission rate. Moreover, the IEEE 802.11ac [1.16] was published in 2013 and the standard realizes transmission rate with 1.3 Gbit/s in 80 MHz channels in the 5 GHz band. Furthermore, the IEEE 802.11 WG established a Study Group (SG) called High Efficiency WLAN (HEW) in May 2013 [1.17]. Meanwhile, HEW SG has become Task Group (TG) in May 2014, that is, TG ax [1.18]. One of the aims of the TG ax is to improve the system throughput characteristics for a certain area in wireless dense environments. The IEEE 802.11ax is now in progress to realize at least four times improvement in the average throughput per STA in a wireless dense environment [1.18]. This scope is not limited to four times improvement. Improvement values in the range of 5-10 times are targeted, depending on technology and scenario.

Taking a comprehensive view of these progress of WLAN systems, the demand of freeing the physical limitation of wired cable is significant issue and employing WLAN system is the one of best solution for the issue. Therefore, WLAN systems are used for all over the world and the demand for enhancement of WLAN performance and features is also being increased. According to this situation, the IEEE802.11 WG promotes the upgrade of WLAN systems by close liaison with external WG or organizations. The relationship between the IEEE 802.11 WG and other organizations and the status of the standardization effort is described in Fig. 1.6 and Fig. 1.7 respectively [1.19].

Fig. 1.4 The Wi-Fi CERTIFIED™ logo.

Table 1.1 List of IEEE 802.11 standards.

Std / TG	Published	Detail
802.11-1997	1997	The first baseline of WLAN.
802.11-2007	2007	The updated baseline including a/b/d/e/g/h/i/j.
802.11-2012	2012	The updated baseline including k/n/p/r/s/u/v/w/y/z.
802.11a	1999	High speed WLAN in 5 GHz.
802.11b	1999	High speed WLAN in 2.4 GHz.
802.11c	Merged	Bridging for different Wireless Networks, merged into 802.1D.
802.11d	2001	Operation at international roaming service.
802.11e	2005	Quality of Service (QoS) enhancement
802.11F	Dropped	Protocol for inter-AP, dropped in 2006.
802.11g	2003	High speed enhancement in 2.4 GHz.
802.11h	2004	Adaption of 11a for Europe.
802.11i	2004	Security enhancement.
802.11j	2004	Adaption of 11a for Japan.
802.11k	2008	Wireless measurement and information exchange.
802.11n	2009	Vigh throughput improvement
802.11p	2010	WLAN for integrated transportation systems (ITS) in the U.S.
802.11r	2008	Fast handover prescription.
802.11s	2011	Mesh network enhancement.
802.11T	Dropped	Examination and measurement for the IEEE 802.11
802.11u	2011	International roaming description with mobile communication systems.
802.11v	2011	Integrated management for WLAN.
802.11w	2009	Security enhancement for management frames.
802.11y	2008	High speed WLAN in 3.6 GHz for the U.S.
802.11z	2010	Enhancement for direct transfer.
802.11aa	2012	Video transfer enhancement.
802.11ac	2013	Very high throughput improvement based on 11n in 5 GHz.
802.11ad	2012	Very high throughput improvement in 60 GHz.
802.11ae	2012	Priority control for management frames.
802.11af	2014	WLAN for TV whitespace.
802.11ah	In progress	Very high speed WLAN in sub-1 GHz for sensor networks.
802.11ai	In progress	Fast initial link setup.
802.11aj	In progress	WLAN using millimeter wave for China.
802.11ak	In progress	General link setup.
802.11aq	In progress	Flexible connection prescription for WLAN devices
802.11ax	In progress	High efficiency WLAN based on 11ac.
802.11mc	In progress	The updated baseline including aa/ac/ad/ae/af.

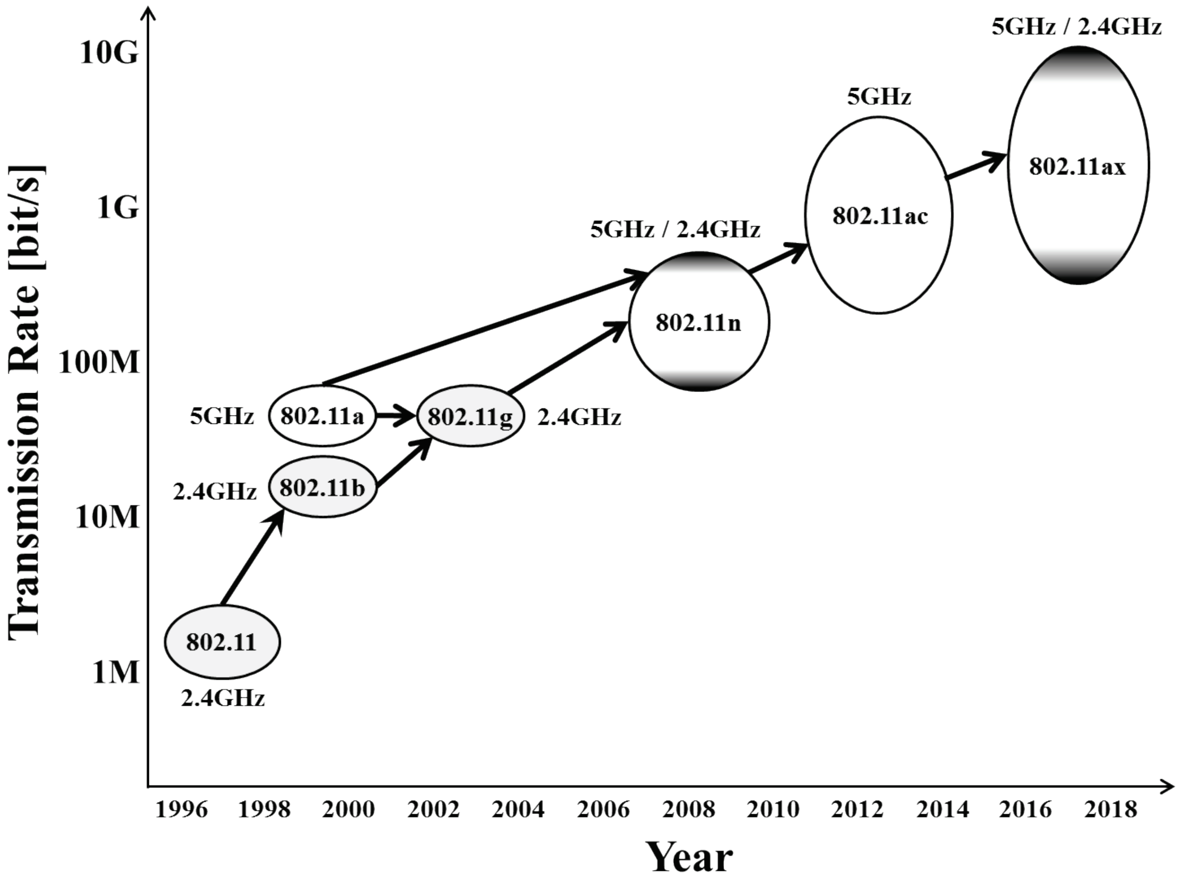


Fig. 1.5 Progress of the IEEE 802.11 standards.

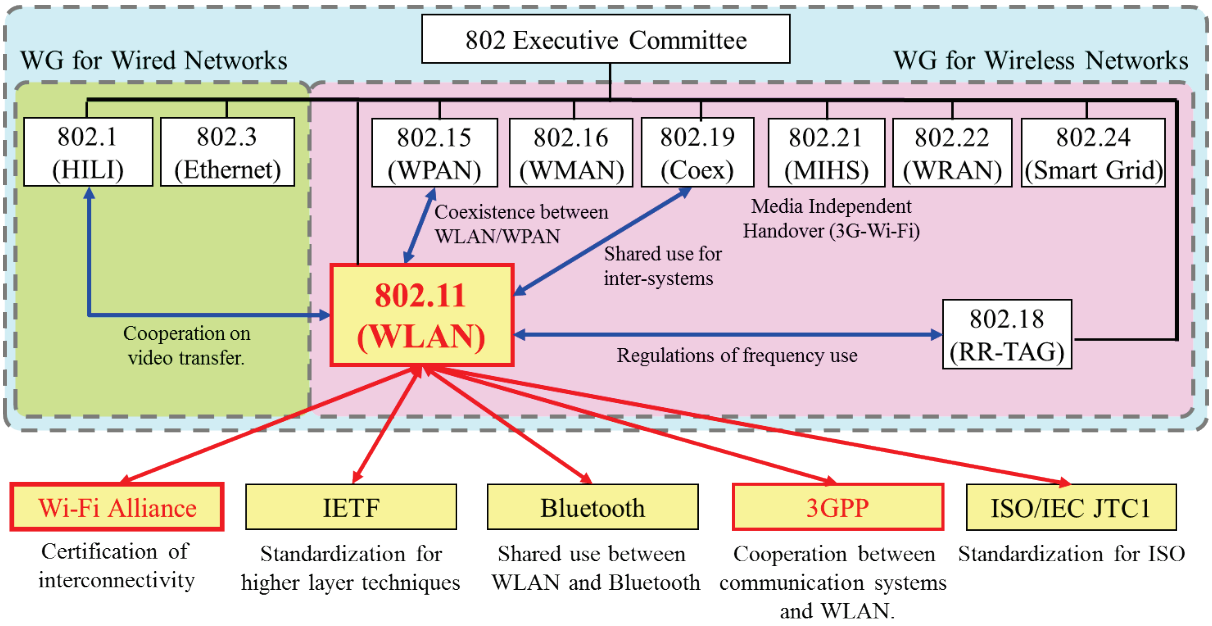


Fig. 1.6 Relationship between the IEEE 802.11 WG and other organizations.

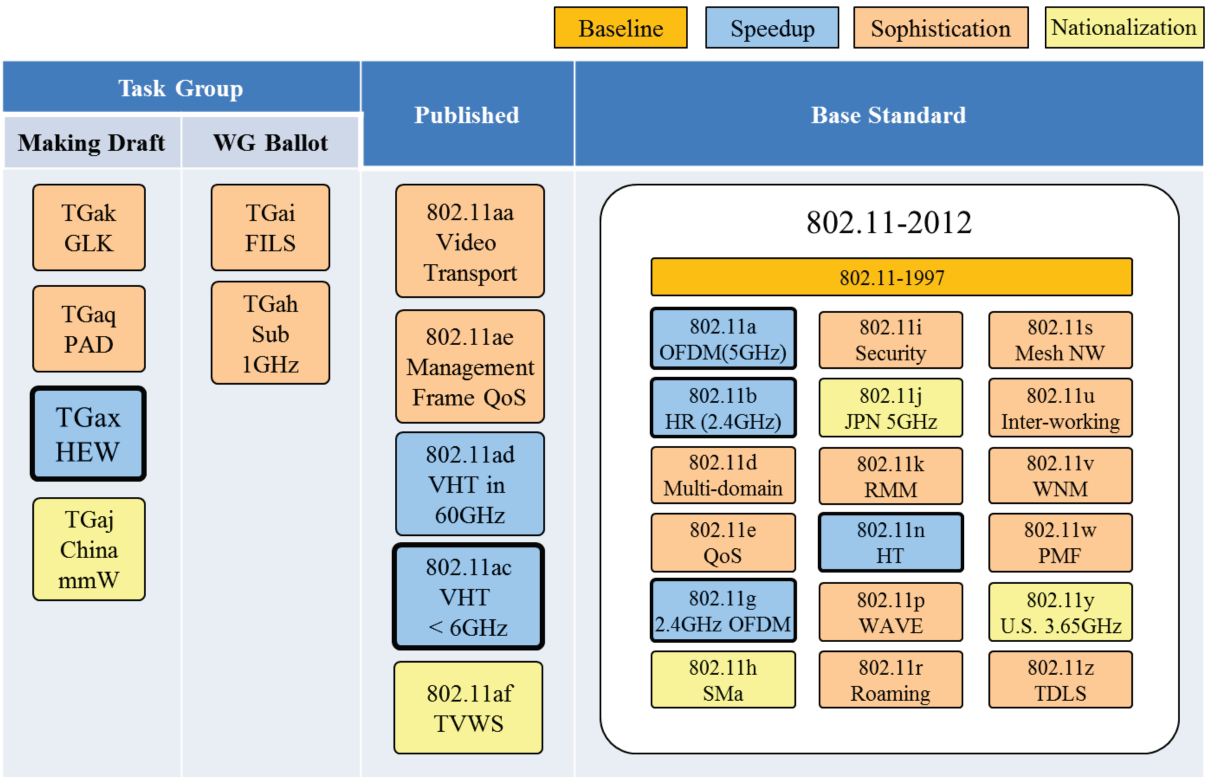


Fig. 1.7 Status of the standardization effort.

1.3. WLAN Networks and Typical Usage Models

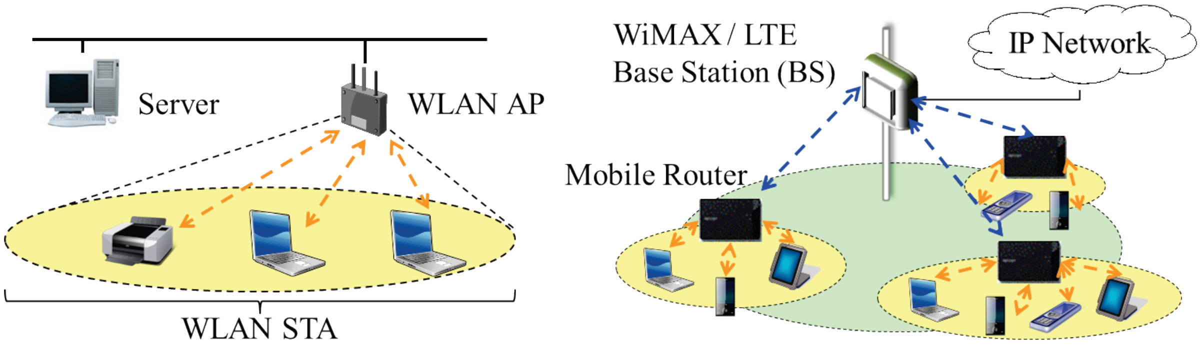
1.3.1. WLAN Network Configurations

The configurations of WLAN systems can be categorized into three types in general, i.e., infrastructure mode, ad-hoc mode, and wireless bridge mode. In infrastructure mode as described in Fig. 1.8, access points (APs) are connected to the Internet via wired networks such as Ethernet or other wireless systems such as Worldwide Interoperability for Microwave Access (WiMAX), LTE or LTE-Advanced, and STAs are connected the APs via WLAN network. This mode is the most popular and general configuration. This configuration is similar to that of mobile communication systems, however the AP is only way for the connection to the Internet and the AP does not control transmission timing and resource allocation for STAs. Although wired networks are the mainstream as the backbone network of an AP that connects the Internet, mobile communication systems are also used as the backbone network in wireless mobile routers. The wireless mobile router is tiny mobile device that equips both interfaces of WLAN and mobile communication systems. Mobile routers enable WLAN devices to connect to the Internet anywhere in the range of mobile communication systems. It works as AP in WLAN and STA in mobile communication systems. The usage model of mobile routers is also a form of infrastructure mode.

In ad-hoc mode as described in Fig. 1.9, the connections between STAs are established autonomously without any AP. In other words, transmitted data is processed between each STA directly in this mode. On the other hand, transmitted data from a STA goes through an AP to communicate with other STA in infrastructure mode. The advantage of ad-hoc mode is flexibility to construct network. This advantage is utilized in sensor networks, machine-to-machine (M2M) networks and in communication system for disaster control.

In wireless bridge mode as depicted in Fig. 1.10, links are established between multiple APs. This configuration is mainly used for transmission relay between a set of WLAN networks when there is no other wired or wireless link among multiple networks. However, this mode is rarely used because backbone networks of infrastructure mode such as optical network systems and mobile communication systems are well installed and operated.

Almost prevailing WLAN services are based on infrastructure mode because of easiness of installation and versatility of connection to the backbone network. Therefore, the network topology of infrastructure mode is mainly discussed in this dissertation.



(a) Wired backbone network

(b) Wireless backbone network

Fig. 1.8　Configuration of infrastructure mode.

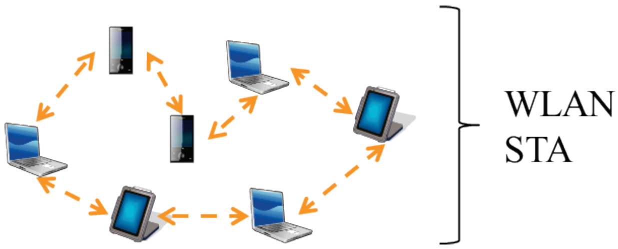


Fig. 1.9　Configuration of ad-hoc mode.

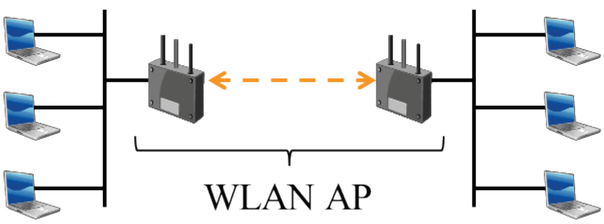


Fig. 1.10　Configuration of bridge mode.

1.3.2. Typical Usage Models

Nowadays, the usage models of WLAN systems are diversified and complicated [1.20][1.21]. The overview of the usage model of WLAN systems is illustrated in Fig. 1.11. STAs which utilize WLAN systems are rapidly increasing for all usage models. This fact generates a lot of wireless dense environment in various usage models.

According to the survey from Japanese government [1.22], more than 40% Japanese houses are apartment. Specifically, the number of apartment dwellings is about 20 million. In these conditions, many WLAN networks installed by the home users operate in high density environment. Most of the home users have one or more WLAN APs. Distance between two APs ranges from 5 to 20 m and the WLAN areas overlap each other. Moreover, Home users have a variety of STAs such as television, personal video recorder, PCs, tablets and gaming machines and access the personal cloud services and Social Networking Service (SNS) over the WLAN networks.

Airports and train stations are typical usage model for public utilization. In those environments, many service providers install their APs and many passengers use WLAN networks. Passengers access the Internet through multiple operators' WLAN network. WLAN network operators may control multiple operators' WLAN networks uniformly. In the typical airport, each AP serves 120 users in a 200 m square and the inter-AP distance is in the range of 15 to 20 m.

Stadiums and exhibition halls are other examples of high density deployment usage models. There may be many WLAN networks installed be the exhibitors, event coordinators and the stadium owners. In these environments, several dozen or hundreds of AP are deployed and each AP may have over a hundred users. Moreover, real-time multimedia services are provided via local contents prepared by the exhibitors or the stadium owners. In such conditions, STAs of the exhibitors, event coordinators and the stadium owners should be prioritized in order to deliver real-time multimedia services or to demonstrate their exhibitions with accuracy. However, the conventional MAC protocol of WLAN systems [1.15] is not designed to control a large amount of STAs in such wireless dense environment and has no function for establishing user level priority control.

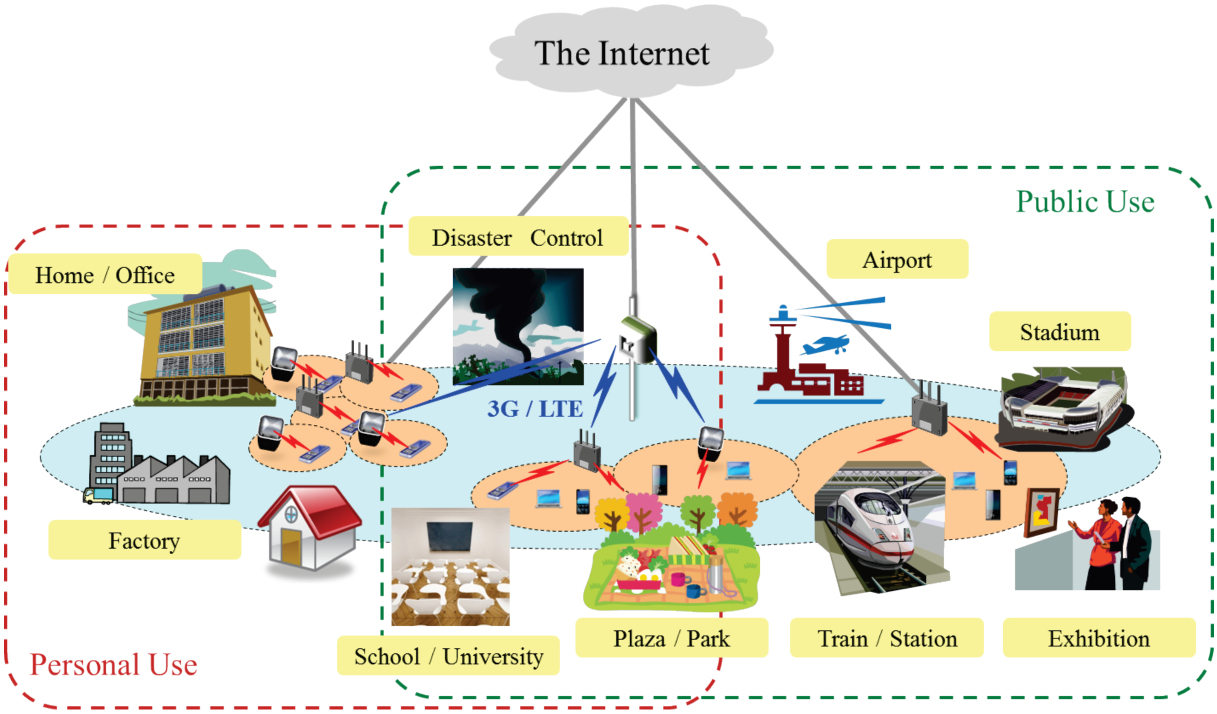


Fig. 1.11 Overview of the usage model of WLAN systems.

1.4. Technical Challenges for WLAN

In wireless communication systems, if two or more STAs transmit signals simultaneously, each signal is interfered with other signals and the receiver may not be able to detect the desired signal correctly. This phenomenon is defined as “co-channel interference” and the situation is defined as “collision”. The co-channel interference generated by collisions is the biggest issue in wireless communication systems including WLAN systems. If the different frequency channel is assigned to each STA, collision is not generated between STAs. Although there are some different frequency channels for WLAN systems, the number of channel is limited due to finiteness of frequency resource. Therefore, WLAN systems allow multiple STA to use same channel for both uplink and downlink. Furthermore, the assignment of channel is overlapped with other channels in 2.4 GHz band. This causes Adjacent-Channel Interference (ACI). The frequency channel assignment of WLAN systems in 2.4 GHz and 5 GHz are illustrated in Fig. 1.12 and Fig. 1.13 respectively. Under the circumstances, many mobile devices equipped with WLAN interface have rapidly proliferated recently as mentioned in Section 1.1. This proliferation is resulting in an increase in congested situations with many WLAN STAs, i.e., wireless dense environment. As the example of actual condition of the wireless dense environment, the whole 2.4 GHz channel condition at Shinagawa station by field investigation in June 2013 is shown in Fig. 1.14. As shown in the figure, many WLAN networks are deployed and these networks overlap their frequency channel without any regulations. Therefore, under these situations, these STAs should be controlled to avoid simultaneous transmission because of the sharing wireless medium among multiple STAs. MAC protocol is a key factor to reduce simultaneous transmissions because it enables each STA to differentiate the timing for transmission. However, contention based protocol such as the CSMA/CA cannot avoid simultaneous transmission completely. Although it is important to eliminate collisions, the MAC protocol for WLAN systems is nearly unchanged from initial version of the IEEE 802.11 standard [1.11].

Most of WLAN systems employ the IEEE 802.11 Distributed Coordination Function (DCF) and the DCF utilize the CSMA/CA as its MAC protocol. The detailed operation of the CSMA/CA is described in Chapter 2. Each STA decides its transmission timing autonomously in the CSMA/CA. This operation is different from mobile communication systems. In mobile communication systems, Base Station (BS) determines transmission timing for each Mobile Station (MS). Therefore, there is no collision between MSs, and the BS can control user level priority for each MS. However in the DCF of WLAN systems, AP does not determine transmission timing for each STA. This mechanism generate following three big issues.

First, as described above, co-channel interference between STAs is generated because of frame collisions that are caused by simultaneous transmissions. In the CSMA/CA, each STA selects random offset timeslot before transmission and this random offset timeslot make difference of the timing for transmission among the STAs. However, the range of the number of timeslot is limited within small number because the conventional WLAN systems do not assume wireless dense environments. Therefore, the probability of frame collision increases in proportion to the number of STAs. If a collision occurs and the frame is not received correctly, the STA which transmitted the collided frame retransmits the frame. This retransmission is necessary for reliable communication but it degrades the performance of communication quality.

Second, Quality of Service (QoS) control for each user cannot be achieved because the CSMA/CA does not have architecture that controls user level priority. If it is the case of mobile communication systems, a BS can allocate frequency resource including duration of transmission and can control the timing of transmission for each MS. Therefore user level priority control is achieved in the systems. However in the CSMA/CA, an AP does not designate transmission timing for each STA. This operation does not ensure the priority control for each user. In other words, the priority for all STAs is impartial in the CSMA/CA. However, to improve the user experience, certain STAs such as those used for presentation at an exhibition, those that connect to a fee-based Wi-Fi hotspot, and site-owned APs should be given priority. In other words, user level priority control should be ensured also in WLAN systems. On the other hand, the IEEE802.11e Enhanced Distributed Channel Access (EDCA) provides a QoS mechanism for WLAN systems. However, the EDCA prioritizes each traffic flow based on categorized applications and not based on specific STAs. In other words, the EDCA ensures application level priority control and does not control user level priority aimed at specified STAs.

Last, WLAN systems suffer from mutual system interference caused by other wireless systems because an AP does not provide any mechanism for protection against the interference. On the other hand, WLAN bring down interference to other wireless systems as well. WLAN systems utilize the ISM radio bands which are recognized as unlicensed bands. Any wireless system that uses unlicensed bands can deploy wireless terminal of the system without any permission. Although it is one of the reasons for significant growth of WLAN systems, this causes mutual system interference between wireless systems which utilize the ISM bands and adjacent bands such as WiMAX. Especially in a wireless mobile router that has the functions of WLAN AP and of WiMAX MS, the emission of the spectrum mask leaks outside the band and caused mutual system interference when the frequency band of WLAN and WiMAX is adjacent. Generally, different frequency channels are assigned for the wireless systems in order not to interfere among multiple systems. However, mutual system interference is generated if the space between each device is very close and if the frequency using each system is adjacent.

To enhance the performance of WLAN systems, these problems should be solved. In order to solve these problems, a lot of physical layer techniques such as a novel adaptive array antenna technique are proposed in Ref. [1.23]. However technologies with little specification impact on the IEEE 802.11 standard are required and implementation impact on hardware should be lessened. Therefore, it is important to enhance MAC protocol that can be realized by software or driver modification.

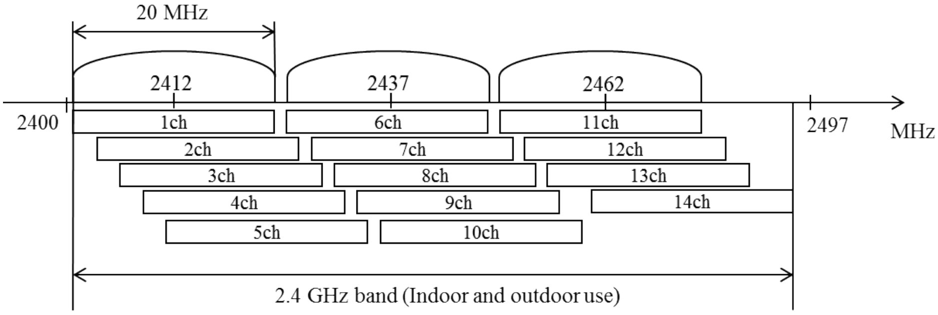


Fig. 1.12 Frequency channel assignment of WLAN systems in 2.4 GHz.

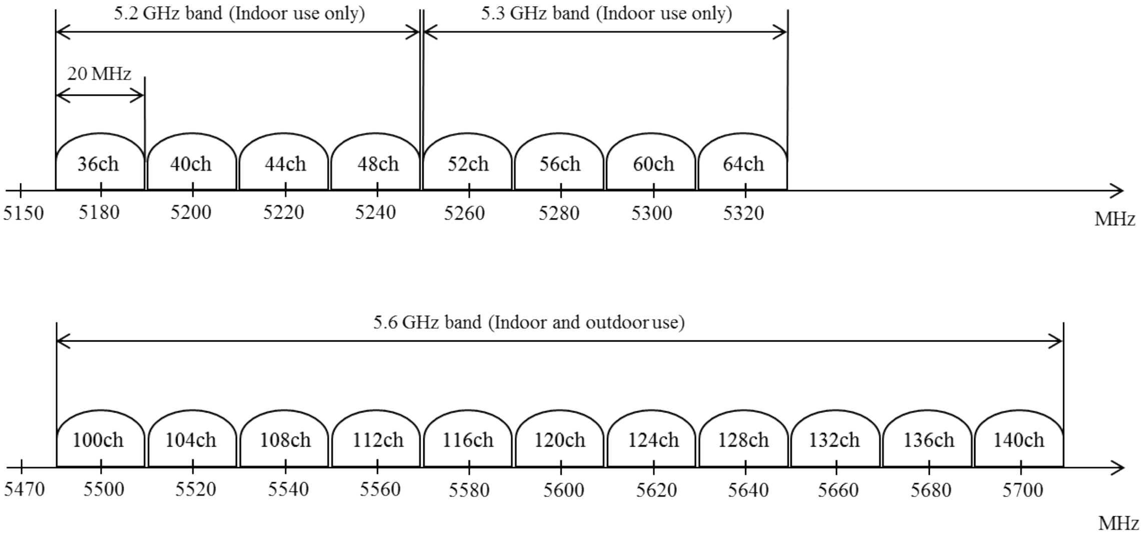


Fig. 1.13 Frequency channel assignment of WLAN systems in 5 GHz.

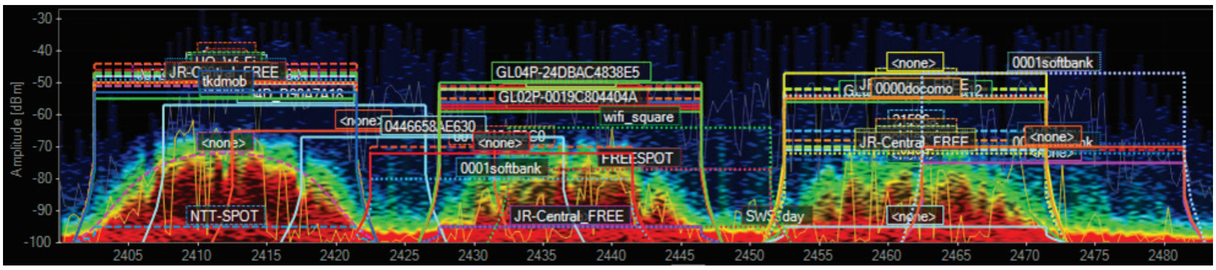


Fig. 1.14 Example of actual condition of the wireless dense environment.

1.5. Communication Quality Improvement on MAC Layer

1.5.1. Advances in Quality of Service

In order to express communication quality, the term of Quality of Service (QoS) is often used. ITU-T Recommendation E.800 [1.24] defines the term of QoS as totality of characteristics of a telecommunications service that bear on its ability to satisfy stated and implied needs of the user of the service. Nowadays, QoS is established as the word that indicates the network performance.

In the early communication systems, differentiation between applications was not a significant issue because types of application were limited. In addition to the reason, transmission rate was very low compared to recent communication systems. However, with the evolution of communication systems, QoS have become important barometer and continuing evolution in the refinement and sophistication in communication systems. In addition, requirements of applications, networks and users have all changed dramatically in the past few years.

Over a century ago, the Public Switched Telephone Network (PSTN) [1.25] started to build out a worldwide circuit switching network for telephone service. This network consisted of fixed-bandwidth dedicated circuits and was ideally suited to carrying real-time traffic, such as voice. After establishing PSTN in five decades, packet switching networks to circumvent any single points of failure were introduced by several researches from military and educational regions. First proposed for military uses in the early 1960s and implemented on small networks in 1968 [1.26]. Packet switching became one of the fundamental networking technologies for most LANs. L. Kleinrock, who proposed Slotted ALOHA, conducted early research in queueing theory which proved important in packet switching [1.27][1.28]. He played a leading role in building and management of the world's first packet switching network, the ARPANET [1.29]. The basic concept of packet switching is to chop the information flow into small chunks, which can be addressed and routed over independent paths to the same destination.

The increased elasticity of packet switching networks caused a shift toward connectionless communications protocols that can handle packets that might arrive out of order. However, for many applications, this was complicated and insufficient. Therefore, connection-oriented protocols such as X.25 [1.30] and Asynchronous Transfer Mode (ATM) [1.31] were developed. In these protocols, a logical circuit is defined over the underlying connectionless packet network to handle a session of communication between two endpoints.

In order to establish the reliable networks for Internet Protocol (IP), non-delayed delivery of real-time traffic on packet switching networks was important. With this background, the concept of traffic classes evolved and packets belonging to these different classes have differentiated for transmission. Early age of IP networks, the concept of a Class of Service (CoS) is introduced in Advanced Peer-to-Peer Networking (APPN) architecture [1.32]. Although CoS used a very different approach from modern QoS, it was the pathfinder of the concept that networking equipment could provide different levels of treatment to particular types of network traffic.

The modern QoS evolution began in the 1990s and developed in the 2000s [1.33]. The predominant traffic types managed on IP networks were voice and data in these days. Voice traffic was real time and comprised constant and predictable bandwidth and packet arrival times. Data traffic was non-real time and comprised unpredictable bandwidth and widely varying packet arrival times. The first attempt to standardize QoS came in the mid-1990s, when the Internet Engineering Task Force (IETF) published the Integrated Services (IntServ) Request for Comments (RFCs) [1.34]-[1.36]. These RFCs based on a signaling protocol called the Resource Reservation Protocol (RSVP). The RSVP informs bandwidth and latency requirements for each discrete session to each node from the sending endpoint to the receiving endpoint. The RSVP was highly impractical over the Internet because it required every node to heed its reservations per-flow state. Therefore, to solve the issue of IntServ, other RFCs [1.37]-[1.42] defined the differentiated Services (DiffServ). The DiffServ describes various behaviors to be adopted by each compliant node and operates on the principle of traffic classification. In DiffServ, each data packet is placed into a limited number of classes, rather than differentiating network traffic based on the requirements of an individual flow in IntServ.

The implementation of QoS architecture on wired networks generally based on the DiffServ, occasionally including an overlay of select IntServ features. However, it is difficult to control QoS with class basis or node basis in wireless networks including WLAN systems due to instability nature of radio propagation. Therefore, the concept of QoS control for WLAN systems was developed based on traffic flow control. The EDCA is typical QoS control method in WLAN systems that based on flow based control and does not control node based QoS. This QoS mechanism defined in the EDCA was established by the IEEE 802.11e in 2005 [1.43].

On the other hand, though there is instability nature of radio propagation, mobile communication systems have been tackled to establish class based QoS control architecture. In addition, almost mobile communication systems were designed based on centralized control in order to manage user level priority for each QoS class. However, as mentioned in Subsection 1.4, node based QoS control was not established in WLAN systems because there were not so many WLAN STAs in past few decades and seamless connection from the backbone wired networks was more important than differentiation of priority between nodes. Therefore, flow based QoS control such as EDCA was developed in WLAN systems.

1.5.2. MAC Layer Approaches for QoS Improvement

As mentioned in Subsection 1.5.1, primary QoS features in WLAN systems was based on flow based control such as EDCA. In addition, a lot of researches were focused on improvement and development of the EDCA. This is because almost STAs in former days were desktop or laptop PCs as described in Subsection 1.1, and this fact indicates that the usage model of WLAN systems was limited to static environment. Therefore, there was little demand for prioritization between STAs based on best effort criterion and the application based control that cooperates with the backbone network was the most important. In such environments, the number of STAs was few and the number of wireless systems that use adjacent ISM band was also few. Due to such conditions, there was sufficient frequency resources and mutual system interference caused by other wireless systems was rarely generated. However, recent changes in circumstances surrounding WLAN systems force to face the issues raised in wireless dense environments as described in Subsection 1.4. In wireless dense environment, communication quality are drastically degraded due to the CSMA/CA manner that was designed without consideration wireless dense environment. Moreover, protection of user level priority aimed at specified STAs has become more important according to variety of usage models. Besides, mutual system interference caused by other wireless systems should be taken into consideration because several new wireless systems such as WiMAX has begun to utilize adjacent ISM bands.

In this dissertation, novel techniques in MAC layer are proposed as solutions for these issues. MAC is part of the link layer in the Open Systems Interconnection (OSI) model illustrated in Fig. 1.15. The OSI model is a conceptual model that characterizes and standardizes the internal functions of a communication system by partitioning it into abstraction layers. The model is a product of the Open Systems Interconnection project at the International Organization for Standardization (ISO), maintained by the identification in Ref. [1.42]. In the OSI model, MAC is central to the proper functioning of any communication system because it defines the procedures of the data transfer in the communication system. The advantages of MAC layer approaches are described as follows. Firstly, backward compatibility can be ensured by improving existing protocols. Secondly, MAC protocols are not realized by electronic circuit modification, signal processing or hardware modification but by driver or software modification. Therefore, easier implementation can be achieved. Finally, node based or user-oriented QoS control can be achieved because MAC protocols handle timing control, transmission scheduling and bandwidth allocation in time domain. Therefore, new MAC layer technologies that can break the difficulties resulting from wireless dense environment in WLAN systems are proposed by this research based on the prior MAC protocols. The issues in changes in the environment of WLAN systems and corresponding proposed techniques are summarized in Table 1.2.

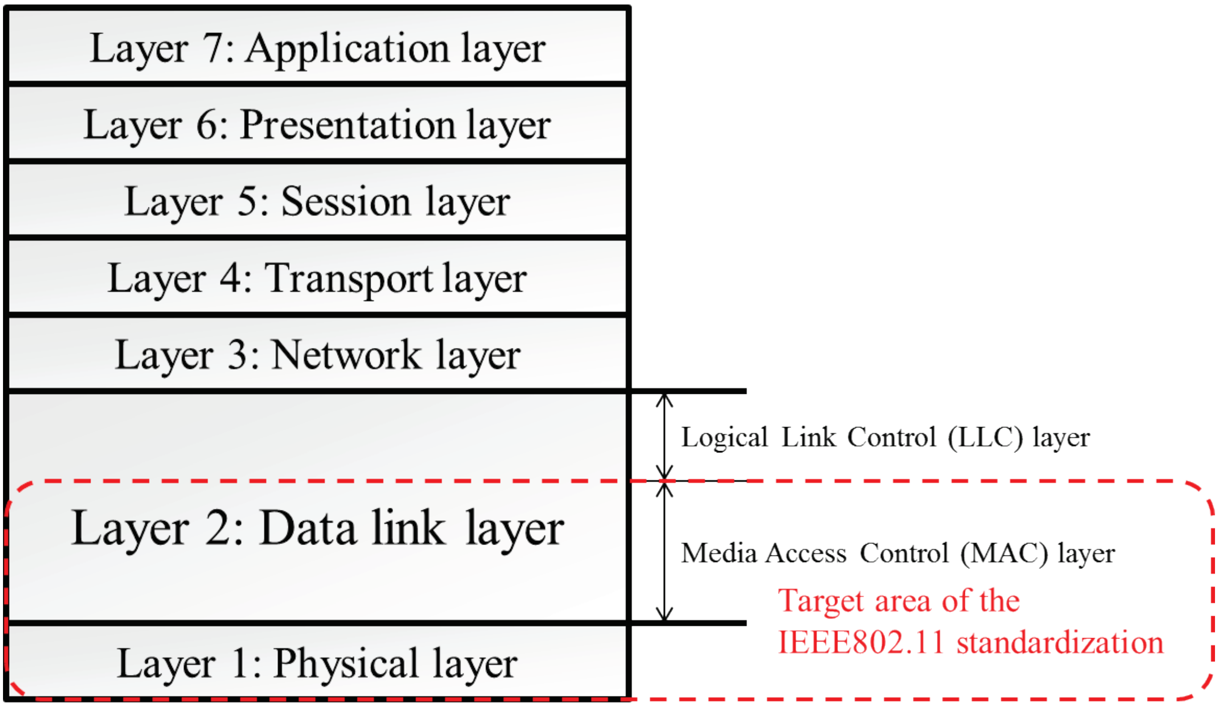


Fig. 1.15 Architecture of OSI model.

Table 1.2 Issues in changes of WLAN systems.

	Past situation	Current situation	Issues	Countermeasure proposed in
The number of STAs are:	few (~10 per BSS)	many (10~ per BSS)	Generation of co-channel interference between STAs because of frame collisions that are caused by simultaneous transmissions	Chapter 3
Requirement of QoS control is:	flow based control only	flow based control + node based control	Establishing QoS control architecture for each user level priority control	Chapter 4
The number of wireless systems that use ISM / adjacent ISM band are:	few	several (WiMAX, Bluetooth, ZigBee, Z-WAVE)	Generation of Mutual system interference between wireless systems	Chapter 5

1.6. Aim of Studies

WLAN systems have achieved remarkable development as described in previous sections. Moreover, studies for improvement of transmission rate and enhancement of functional features have been investigated for a few decades. However, transformation of usage of WLAN systems generates wireless dense environments and this fact causes new unprecedented issues for WLAN systems described in Section 1.4. Therefore, the aim of this dissertation is to propose novel techniques that can solve the issues. Moreover, those techniques should have backward compatibility with the conventional IEEE 802.11 standards. In this dissertation, following three techniques are introduced to solve the fundamental issues raised in Section 1.4.

1) To reduce heavy collisions between STAs that cause co-channel interference, a simple and adaptive frame collision control scheme that can mitigate severity of contention for obtaining channel access is proposed. This technique is achieved by refraining from transmission for certain duration that based on the condition of wireless dense environment after successful transmission. Moreover, this mechanism improves the system performance without drastically changing the existing CSMA/CA and the definition in the IEEE 802.11 standards.

2) To establish a control mechanism of user level priority for WLAN systems, a pseudo-centralized control technique that enables control of flexible bandwidth allocation to each specific STA is proposed. This technique is realized by designating two kind of fixed back-off time for each STA and the technique enables to control the priority level and can coexist with the conventional CSMA/CA. Moreover, the system performance is also improved by its pseudo-centralized control mechanism that reduces frame collisions.

3) To avoid mutual system interference between WLAN and WiMAX systems, a scheduling technique that controls timing of transmission for WLAN systems is proposed. This technique is achieved by leveraging the PSMP function defined in the IEEE802.11 standard. Moreover, this mechanism realizes simultaneous transmission for both WLAN and WiMAX systems and mitigate outbreak of mutual system interference.

Those results will be useful when designing the next generation of WLAN systems. Moreover, the concrete mechanism of MAC protocols should contribute to shortening the time needed to realize such systems.

The organization of this dissertation is shown in Fig. 1.16. This dissertation consists of six chapters.

Chapter 1, “Introduction”, describes the background, the historical progress of WLAN systems, the technical challenges and the purpose of dissertation.

Chapter 2, “Overview of MAC Protocols for WLAN”, explains the mechanism of existing MAC protocols of the IEEE 802.11 WLAN systems and mentions the importance of MAC layer approach.

Chapter 3, “Frame Collision Reduction Scheme for Wireless Dense Environment”, proposes a simple scheme that decreases the number of frame collisions for WLAN systems. After a successful transmission, the proposed scheme refrains from transmission during certain time which is defined as Post-Inter Frame Space (Post-IFS). The length of the Post-IFS is a key factor in improving the system performance for the proposed scheme. If the AP can estimate the optimal value of the Post-IFS, collision-free operation similar to that in a non-contention based protocol is performed. Even if the optimal Post-IFS is not estimated, the number of competing STAs and the collision probability are decreased. This mechanism improves the system performance including the throughput characteristics and access delay by reducing the number of competing STAs.

Chapter 4, “User-Oriented QoS Control Scheme based on CSMA/CA”, proposes a flexible pseudo-centralized control scheme by using two kinds of fixed back-off value for back-off time. The proposed scheme is based on the CSMA/CA and the basic MAC function are same as the CSMA/CA. The significant difference between the CSMA/CA is how to decide back-off value. Though the CSMA/CA decides back-off value by random within the Contention Window (CW) range, the proposed scheme defines and adopts two kinds of fixed back-off value, namely, “Initial Back-off Value (IBV)” and “Cyclic Back-off Value (CBV)”. This mechanism enables to control the user level priority and to improve the system performance including the throughput characteristics, access delay and the number of retransmission.

Chapter 5, “Interference Avoidance Scheme for Wireless Mobile Routers”, proposes an interference avoidance technique that allows wireless device with similar frequency bands to be operated adjacent to each other for compact wireless mobile routers. This wireless mobile router implements two devices of WLAN and WiMAX systems. The wireless mobile router connects WLAN STAs to the backbone network by using WiMAX-WLAN relay. In the wireless mobile router, mutual system interference is generated because the space between each device is very close and the frequency using each system is adjacent. To suppress this interference, the proposed scheme leverages the IEEE 802.11 PSMP. The conditions that raise the issues of mutual system interference are clarified by experiments. Moreover, simulations are conducted to show that the proposed scheme outperforms the conventional schemes.

Chapter 6, “Conclusions”, describes the conclusions reached and summarizes the performance of techniques proposed in this dissertation.

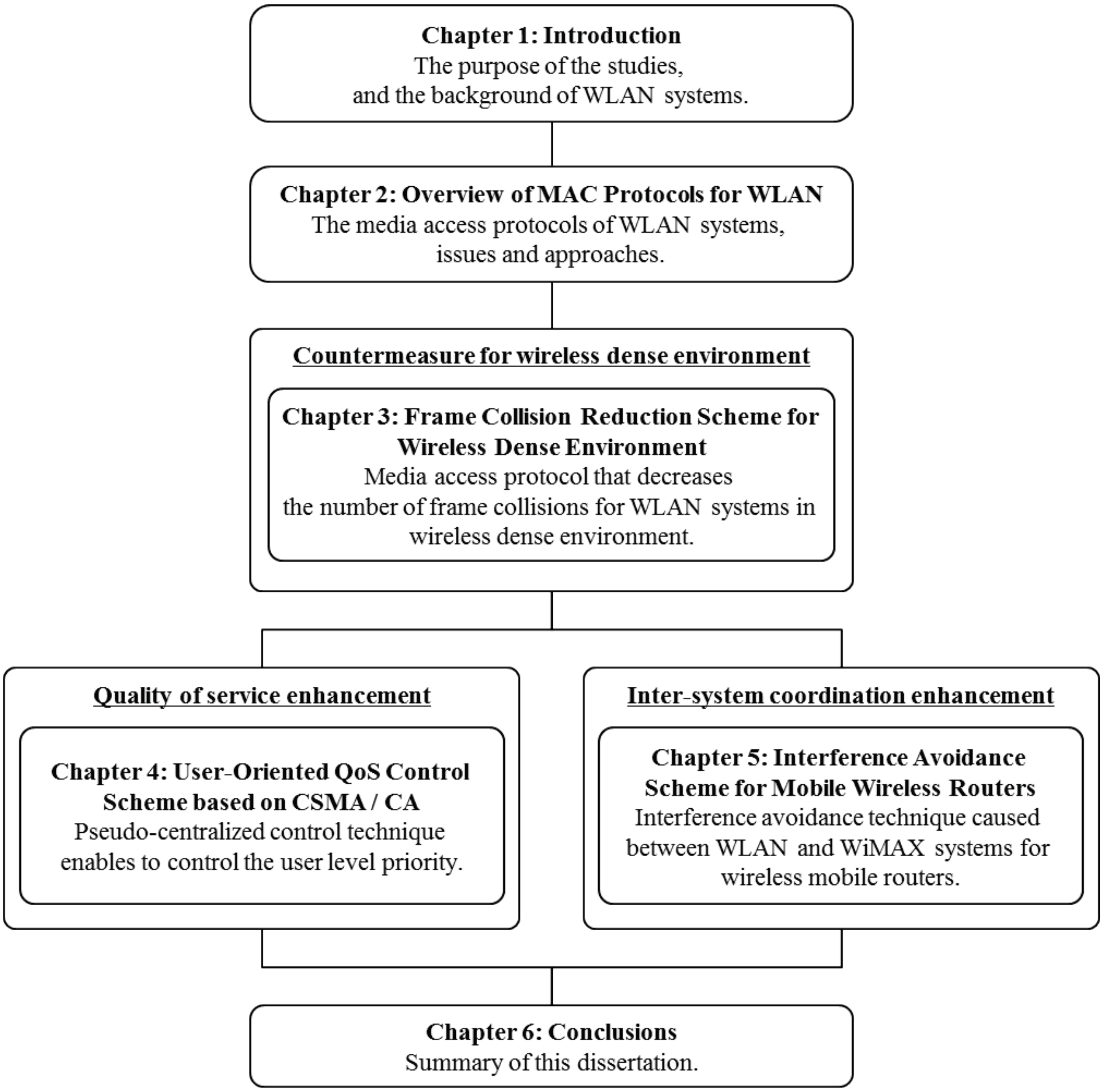


Fig. 1.16 Organization of this dissertation.

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Chapter 2

Overview of MAC Protocols for WLAN

2. Overview of MAC Protocols for WLAN

2.1. Introduction

This chapter gives an overview of the fundamental MAC protocols that defined in the IEEE802.11 standard [2.1]. Moreover, the issues and existing approaches on MAC protocols for WLAN systems are explained.

All the MAC protocols of WLAN systems are based on TSS that shares the same medium for communications and each STA segregates its transmission timing by Time Division Multiple Access (TDMA) manner or Random Access (RA) manner [2.2]. Almost every STA obey the DCF that utilizes the CSMA/CA for its MAC protocol because the DCF provides flexible deployment for WLAN systems. Although there is an AP in the network, any coordinator that manages the timing of transmission for each STA is not required in the DCF. Moreover, the CSMA/CA is a contention based protocol, where the term "contention" is interpreted as "There is possibility of generating frame collisions in the same network". Although collisions are generated in the CSMA/CA, the CSMA/CA has high feasibility for operation of data exchange and is not disrupted in any situation according to its distributed autonomous control.

On the other hand, the IEEE 802.11 standard introduces non-contention based protocols such as the PCF, the HCCA and the PSMP [2.1], where the term "non-contention" is interpreted as "The timing of transmission for each STA is managed and there is no possibility of generating frame collisions in the same network". In those protocols, an AP performs a role of a coordinator that manages and schedules the timing of transmission for each STA. Those non-contention based protocols outperform contention based protocols in throughput characteristics by eliminating any collisions. However, there are a number of drawbacks in those non-contention based protocols [2.3]. One major drawback is the potential delay because each STA must wait for its next transmission timing until the end of the scheduled transmission period for all STAs. This can severely impact delay sensitive traffic. Another drawback of the non-contention based protocols is that those protocols do not work well if used on neighboring networks sharing the same channel. If one non-contention protocol is in progress on one network a neighboring network would need to wait for that protocol to end before beginning its own scheduling. These are fatal drawbacks to deploy WLAN STAs autonomously, especially in unlicensed band. Therefore, non-contention based protocol are rarely used in actual WLAN systems nowadays.

Those MAC protocols that are employed in the IEEE 802.11 are explained in Section 2.2. Besides, classification of those protocols is illustrated in Fig. 2.1.

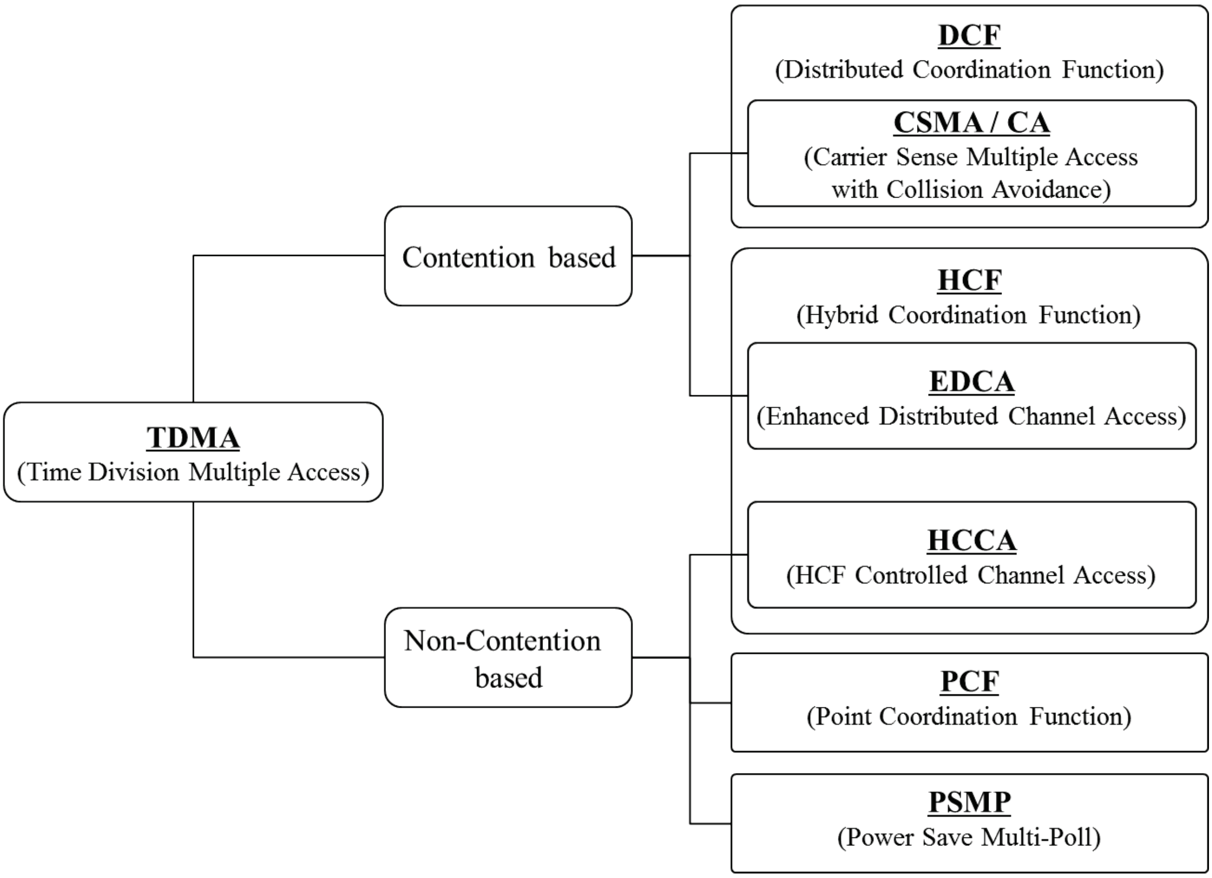

Fig. 2.1 Classification of IEEE 802.11 MAC protocols

2.2. Media Access Control Protocols for WLAN

2.2.1. Distributed Coordination Function (DCF)

The DCF is the basic function of the IEEE 802.11 based on the CSMA/CA that allows for automatic medium sharing between STAs by using random back-off time following a busy medium condition. The CSMA/CA is a contention based protocol and is implemented in various devices because STAs can operate autonomously without a coordinator that manages the transmission timing for each STA. In this dissertation, the CSMA/CA is assumed as the conventional scheme hereafter and a STA which obey the conventional DCF feature is defined as a DCF STA. Although the CSMA/CA allows flexible and feasible operation, the system performance is severely degraded in a wireless dense environment due to the number of collisions generated between STAs.

In order to explain the operation of the CSMA/CA employed in the IEEE 802.11, the basis of the CSMA is described first. In the CSMA, STAs autonomously decide the transmission timing. If the wireless channel is in use for any STA or other wireless systems, the other STAs recognize the channel as being "busy" and defer transmission. Subsequently, if no other STA uses the channel, the STAs recognize the channel as being "idle" and may attempt transmission. This mechanism that a STA detects the condition of the wireless channel is called as Carrier Sense (CS). At this point, there are two types of mechanism for the CSMA according to the determination of the timing for transmission, that is, the non-persistent CSMA and the *p*-persistent CSMA.

The basic operation of the non-persistent CSMA is illustrated in Fig. 2.2. In the non-persistent CSMA, A STA halts its CS when the transmission channel is busy, afterwards, the STA retries its CS after waiting certain duration. When the transmission is failed due to a collision, the STA defers its transmission for random duration and reattempts CS process after the duration ends. Normalized throughput S of the non-persistent CSMA is calculated as follows [2.4],

$$S = \frac{Ge^{-aG}}{G(1+2a)+e^{-aG}}. \tag{2.1}$$

In Eq. (2.1), G represents offered traffic determined by Eq. (2.2),

$$G = \lambda T. \tag{2.2}$$

Here, λ denotes average sporadic rate of a data frame per second in the Poisson distribution and T is time for the length of a data frame. Besides in Eq. (2.1), a is calculated from propagation delay time τ and T as follows,

$$a = \frac{\tau}{T}. \tag{2.3}$$

Another type of CSMA is the *p*-persistent CSMA. The basic operation of the *p*-persistent CSMA is illustrated in Fig. 2.3. In the *p*-persistent CSMA, A STA continues its CS when the transmission channel is busy. When the channel becomes idle, the STA tries to execute its transmission with probability *p*. At this point, *p* equals 1, or the case that the STA transmit a frame certainly whenever the channel becomes idle is called as the 1-persistent CSMA. Normalized throughput *S* of the 1-persistent CSMA is calculated as follows [2.5],

$$S = \frac{G\left[1 + G + aG\left(1 + G + \frac{1}{2}aG\right)\right]e^{-G(1+2a)}}{G(1+2a) - \left(1 - e^{-aG}\right) + (1 + aG)e^{-G(1+a)}}. \tag{2.4}$$

The DCF utilizes hybrid concept of the non-persistent CSMA and the 1-persistent CSMA. If the channel is idle for duration of a DCF Interframe Space (DIFS) or more, a STA can access the channel immediately like the non-persistent CSMA, otherwise the STA continues CS and defers access prior to the transmission like the 1-persistent CSMA. Fig. 2.4 shows the basic operation of the CSMA/CA utilized for the DCF in the IEEE 802.11 standard. It is consist of following features.

1) **Interframe Space (IFS):** The IFS is defined time interval between frames. Six different IFSs are defined to provide priority levels for access to the wireless medium. The IFSs are:

   a) Reduced Interframe Space (RIFS)
   The RIFS has a shortest length of the IFSs between transmissions from a single STA and is used for reducing overhead in order to increase network efficiency. RIFS may be used in place of SIFS to separate multiple transmissions from a single STA. This IFS is defined in the IEEE 802.11n but is not used for the IEEE 802.11ac.

   b) Short Interframe Space (SIFS)
   The SIFS is the shortest of the IFSs between transmissions from different STAs. SIFS shall be used when STAs have seized the medium and need to keep it for the duration of the frame exchange sequence to be performed. Using the smallest gap between transmissions within the frame exchange sequence prevents other STAs, which are required to wait for the medium to be idle for a longer gap, from attempting to use the medium, thus giving priority to

completion of the frame exchange sequence in progress.

c) <u>PCF Interframe Space (PIFS)</u>

The PIFS consists of SIFS and a slottime. At this point, a slottime is defined as a time unit that is necessary for CS, intermediate switching, air propagation time and processing delay. PIFS is mainly utilized for non-contention based protocol for the IEEE 802.11 such as the PCF.

d) <u>DCF Interframe Space (DIFS)</u>

The DIFS consists of SIFS and two slottime. DIFS is used for CS prior to transmitting a frame. IFSs excluding RIFS and SIFS can execute CS within its slottime.

e) <u>Arbitration Interframe Space (AIFS)</u>

The AIFS consists of SIFS and multiple slottime according to the priority of a transmitting frame following after AIFS. AIFS is utilized instead of DIFS for the IEEE802.11e EDCA that provides an application level priority control for WLAN systems. The shorter AIFS grants high priority for the transmission, and the longer AIFS gives low priority as well.

f) <u>Extended Interframe Space (EIFS)</u>

The EIFS is derived from SIFS, DIFS and the length of time it takes to transmit an ACK frame at the lowest mandatory transmission rate determined by the IEEE 802.11 standard. After receiving a frame that destined to other STAs, each STA defers access for EIFS duration not to interrupt and to keep fair competition for gaining channel access.

2) **Random Back-off:** When the STA transmits a frame, the STA generates a random back-off time for an additional deferral time. This process reduces collisions during contention for channel access between multiple STAs. The back-off time is decided by multiplication of random value and slottime and the random value is defined as back-off value. The back-off value is randomly assigned from the range of the Contention Window (CW). The DCF adopts Binary Exponential Back-off (BEB) to select this CW. At the first transmission, the CW is assigned to the initial value, CW_{min}. If transmission failures continue, the CW increases exponentially up to the upper bound, CW_{max}. In addition, the CW is reset to CW_{min} when the transmission succeeds. Therefore, the CW is decided based on the BEB as follows,

$$CW = \min[(CW_{\min} + 1) \times 2^{n_{ret}} - 1, \quad CW_{\max}]. \tag{2.5}$$

In Eq. (2.5), n_{ret} denotes the number of retransmissions. An example of the operation of back-off procedure is shown in Fig. 2.5.

3) **Acknowledgement (ACK):** After transmitting a frame that requires an ACK frame, the receiver shall send an ACK frame as a response for the transmitted frame. The transmitter identifies the success and failure of the transmission by means of the existence of the ACK frame. The transmitter shall wait for an ACK timeout interval defined in the standard in order to anticipate the reception of the ACK frame.

In wireless dense environments, due to the limitation of the range of CW, the probability that two or more STAs select the same back-off value increases and that results in generating collisions. In particular, if the number of competing STAs that attempt transmission exceeds the CW, a collision between STAs is inevitable. Furthermore, although the probability of collision decreases temporarily as the CW increases due to a transmission failure according to the BEB, the probability of collision increases again because the CW is reset to CW_{min} when the transmission succeeds.

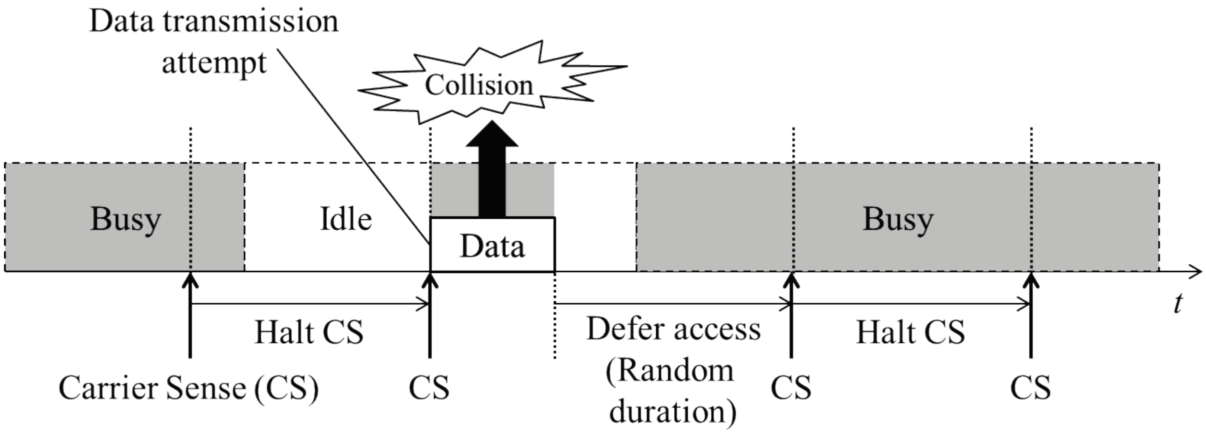

Fig. 2.2 Concept of non-persistent CSMA.

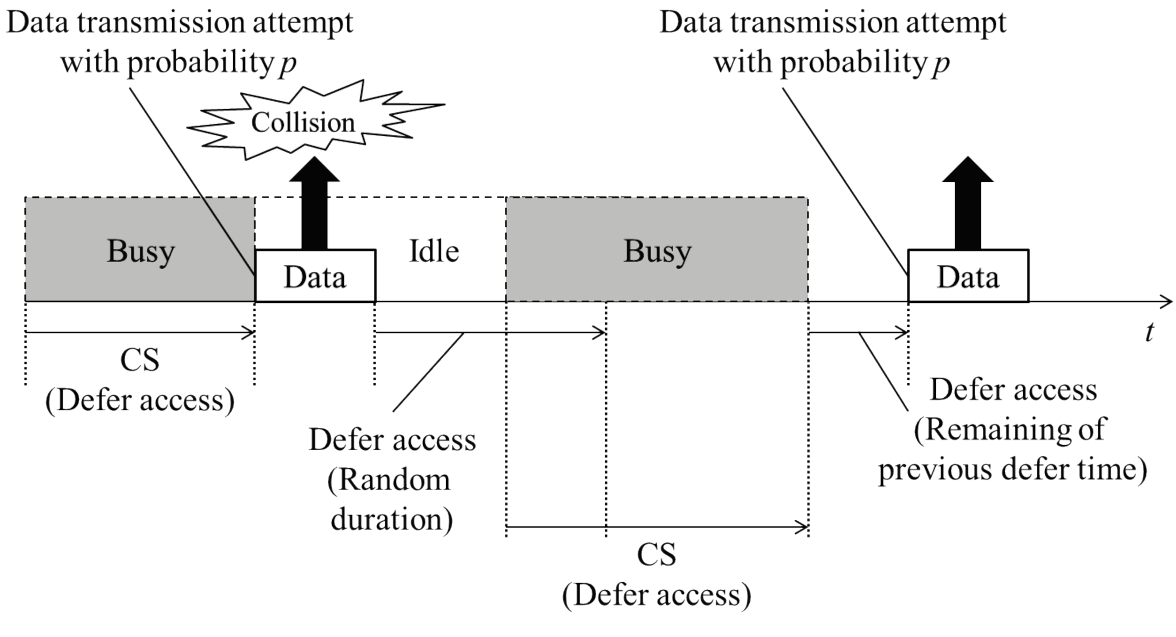

Fig. 2.3 Concept of *p*-persistent CSMA.

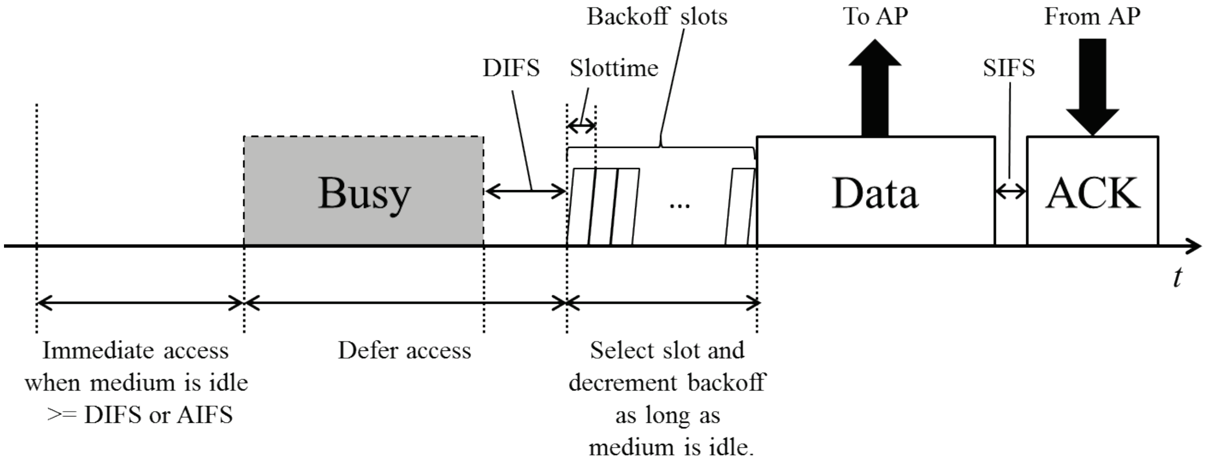

Fig. 2.4 Basic operation of CSMA/CA.

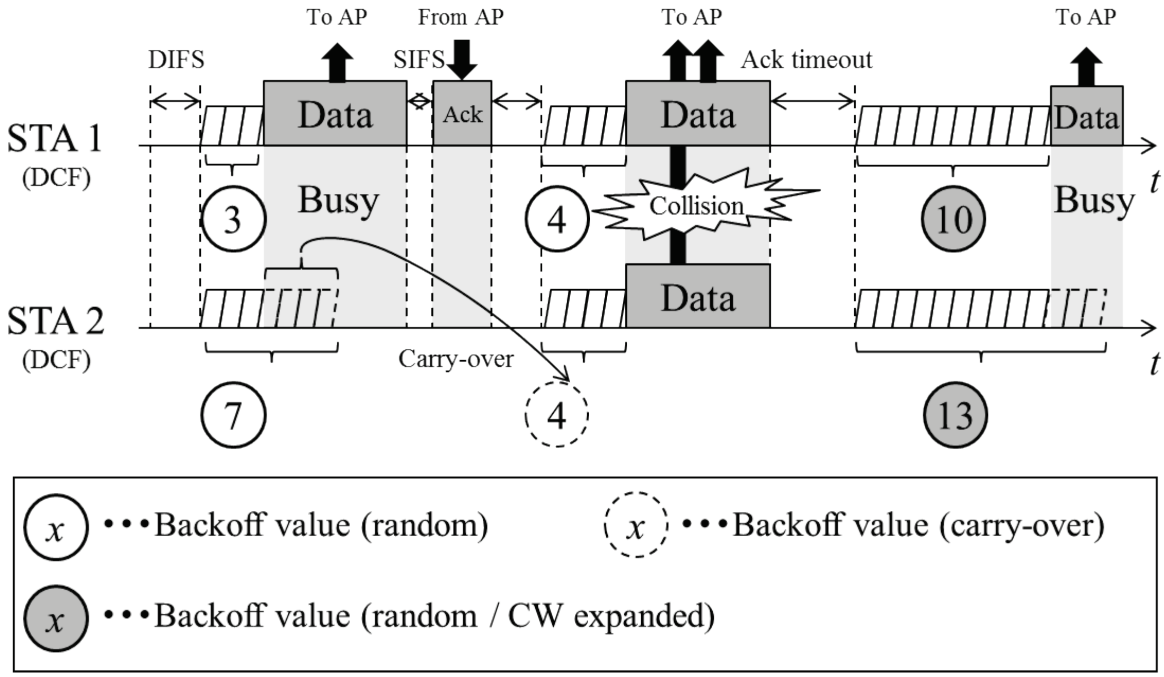

Fig. 2.5 Operation of back-off procedure.

2.2.2. Point Coordination Function (PCF)

The PCF is optional feature of the IEEE 802.11standard [2.1]. The PCF is a non-contention based protocol that requires a coordinator managing the timing of transmission for each STA. The coordinator is defined as Point Coordinator (PC) in the PCF and an AP plays a role of the PC. The PCF divides communication period into two phases, one is the Contention Free Period (CFP) and the other is Contention Period (CP). In the CFP, the PC designates the timing of transmission specifically for each STA, and in the CP, each STA controls the timing of transmission autonomously based on the DCF manner. Therefore, the PCF is technically defined as a hybrid of non-contention based and contention based protocol. However, as the greatest feature of the PCF is non-contention based control, the PCF is categorized into a non-contention based protocol in this dissertation. Besides, the same holds for the HCCA.

The basic operation of the PCF is shown in Fig. 2.6. The PC gains control of the wireless medium at the beginning of the CFP and attempts to maintain control for the entire CFP by sending a Beacon frame. This Beacon frame is transmitted after waiting for PIFS. All STAs that receive Beacon frames containing the PCF related parameters, including STAs not associated with the PC, set their Network Allocation Vectors (NAVs) to the maximum duration of CFP. At this point, the NAV indicates the duration that STAs must defer their transmission regardless of whether the wireless medium is busy. This mechanism is called as Virtual Carrier Sense (VCS). The NAV is set to all STAs other than designated STA that allows executing transmission. The PC uses polling frames in order to indicate the timing of transmission for each STA, the beginning and the end of the CFP. Moreover, Data frames and ACK frames from the PC can be combined with the polling frames as described in Fig. 2.6. The PCF has good throughput characteristics due to eliminating back-off time and combining the frames [2.6]. During the CP after the CFP, transmission procedure of each STA obeys the CSMA/CA described in Section 2.2.1.

In the PCF, the beginning of the CFP is inevitably associated with the beginning of a Beacon frame that the AP broadcasts periodically in order to inform the parameters of the WLAN network. Therefore, if the timing of transmission for a Beacon frame is overlapped with that of another WLAN network using the PCF, the entire PCF mechanism will be collapsed. This is the most serious issue of the PCF.

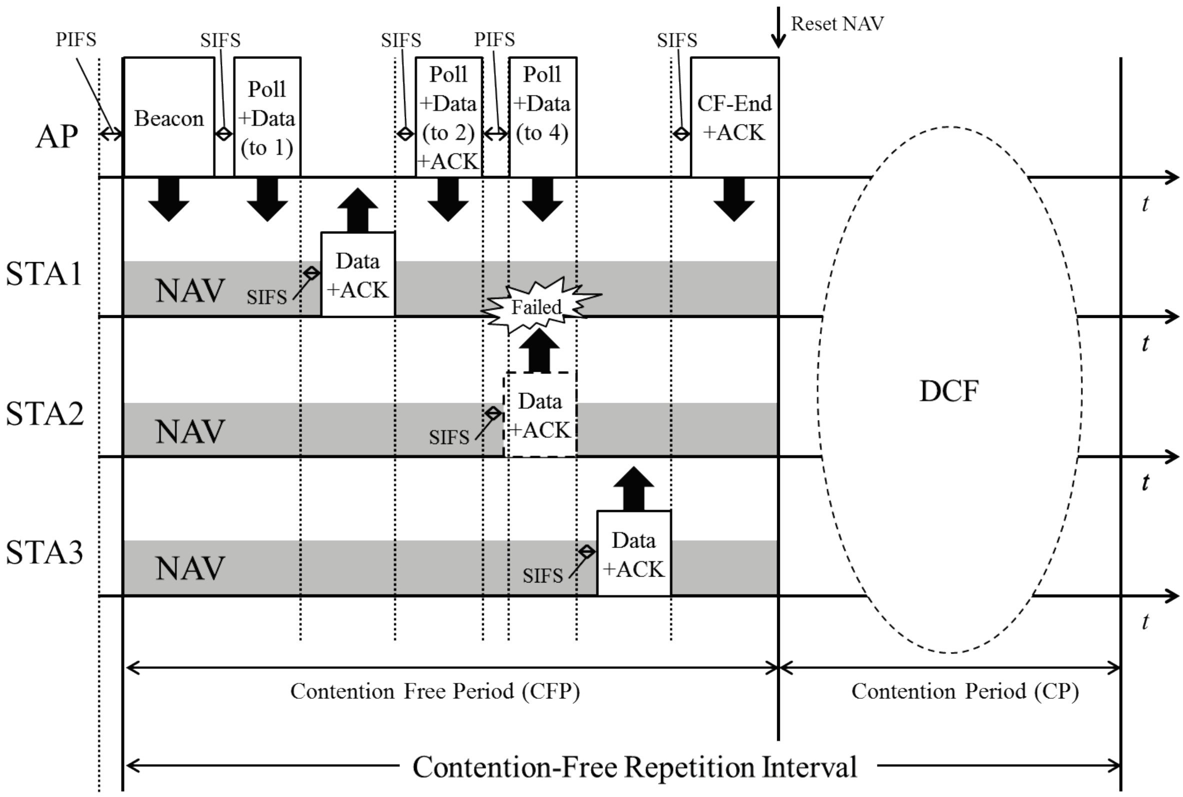

Fig. 2.6 Basic operation of PCF.

2.2.3. Hybrid Coordination Function (HCF)

The HCF is defined in the IEEE 802.11e that aimed at establishing QoS support for WLAN systems. The HCF consists of a contention based protocol (EDCA) [2.7] and a non-contention based protocol (HCCA). Under the HCF, the basic unit of allocation of the right to transmit onto the wireless medium is the Transmission Opportunity (TXOP). Each TXOP is defined by a starting time and a defined maximum length. The TXOP may be obtained by a STA winning an instance of an EDCA contention or by a STA receiving assignment for channel access from a coordinator of the HCCA. The brief descriptions of the EDCA and the HCCA are given in this section.

1) **Enhanced Distributed Channel Access (EDCA):** This function is also called as the HCF contention-based channel access. The EDCA provides a mechanism for application level priority control [2.8]. In the EDCA, AIFS is used instead of DIFS for QoS STAs in order to differentiate the level of QoS. Access categories (ACs) are defined as a function of the QoS in the EDCA and each AC has different AIFS and CW parameters as shown in Table 2.1. In the table, aCW_{min} is the default value for the CW_{min} defined in the standard [2.1] and this value is 15 in the DCF. The duration of AIFS[AC] is derived from the value AIFSN[AC] by the following relation,

$$\mathrm{AIFS[AC]} = \mathrm{AIFSN[AC]} \times \mathrm{slottime} + \mathrm{SIFS}. \tag{2.6}$$

As described in Section 2.2.1, the shorter AIFS grants high priority for the transmission, and the longer AIFS gives low priority as well. The default parameters of the EDCA for each AC in the IEEE 802.11 standard [2.1] are described in Table 2.2. Moreover, STAs have queues corresponding to each AC, and each traffic flow is inserted into the queue corresponding to an application. The basic operation and queue model of the EDCA is illustrated in Fig. 2.7 and Fig. 2.8 respectively.

2) **HCF Controlled Channel Access (HCCA):** The HCCA provides non-contention mechanism and basic concept is similar to that of the PCF. However, in contrast to the PCF, in which the interval between two beacon frames is divided into two periods of the CFP and the CP, the HCCA allows for non-contention period being initiated at almost any time during a CP. This kind of CFP is called a Controlled Access Phase (CAP). A CAP is initiated by the AP whenever it wants to send a frame to a STA or receive a frame from a STA. The AP which manages the CAP is defined as Hybrid Coordinator (HC) in the HCCA. The concept model of the HCCA is described in Fig. 2.9. The HC gains control of the wireless medium according to demand of sending QoS traffic and it realizes by issuing CF-Poll frames to STAs. The CF-Poll frame is sent by waiting a shorter time

between transmissions than the STAs using the EDCA procedures. At this point, the QoS characteristics of a data flow from a QoS STA are admitted in advance of CAP by using Traffic Specification (TSPEC) negotiation function. Moreover, the HC may initiate the CFP based on the PCF procedure aside from the procedure of the CAP.

Thus, the HCCA establishes flexible control and significantly improves the PCF [2.9]. However, it has not been widely implemented as well as the PCF. To ensure demanding quality, the HC has to establish a schedule and based on that schedule gains regular priority access to the wireless medium using the PIFS defer. However, this mechanism breaks down in the presence of neighboring WLAN networks using the HCCA. If the HCs of both networks are attempting to gain channel access then there may be frequent collisions. This is the same issue for the PCF.

Table 2.1 ACs and CW parameters for EDCA.

AC	CWmin	CWmax
Background (AC_BK)	aCWmin	aCWmax
Best Effort (AC_BE)	aCWmin	aCWmax
Video (AC_VI)	(aCWmin+1) / 2 - 1	aCWmin
Voice (AC_VO)	(aCWmin+1) / 4 - 1	(aCWmin + 1) / 2 - 1

Table 2.2 Default parameters for EDCA.

AC	CWmin	CWmax	AIFSN	Max TXOP [ms]
Background (AC_BK)	15	1023	7	0
Best Effort (AC_BE)	15	1023	3	0
Video (AC_VI)	7	15	2	3.008
Voice (AC_VO)	3	7	2	1.504
DCF	15	1023	2	0

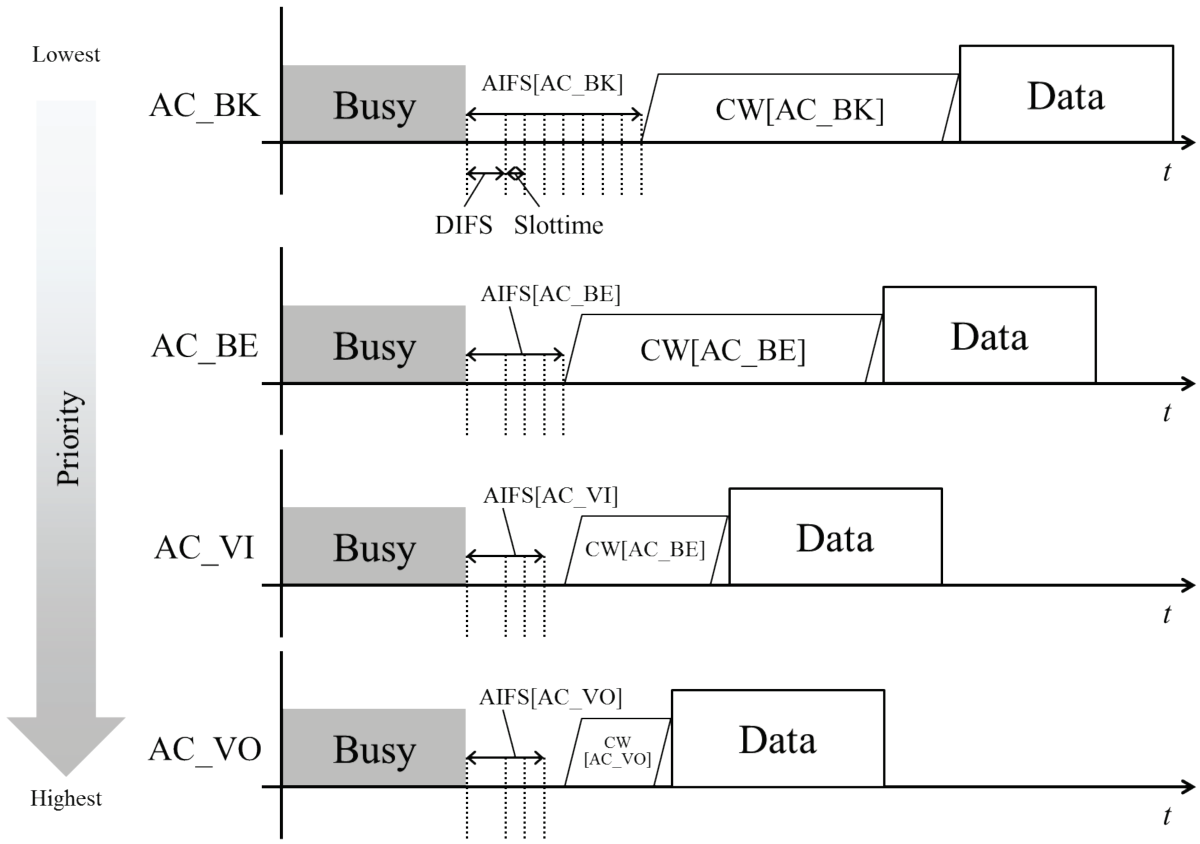

Fig. 2.7 Basic operation of EDCA.

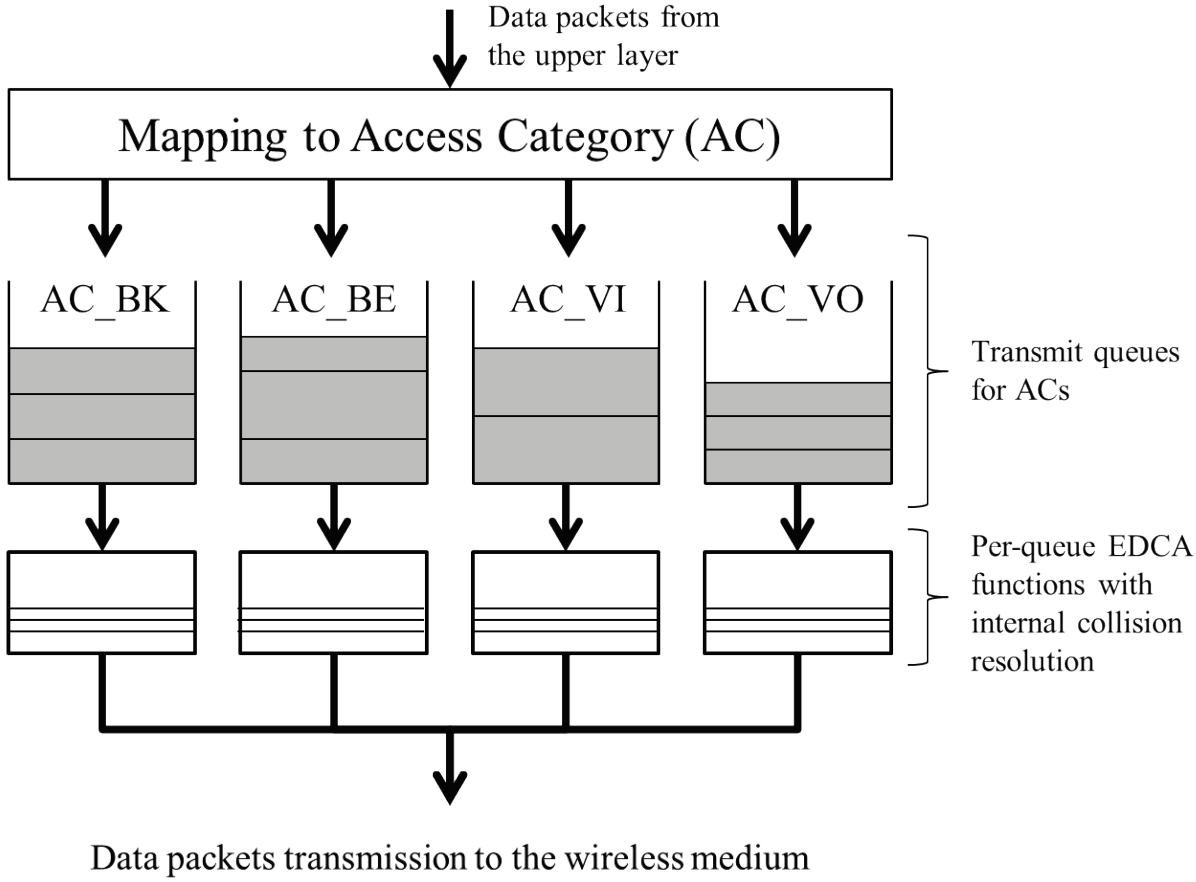

Fig. 2.8 Reference queue model of EDCA.

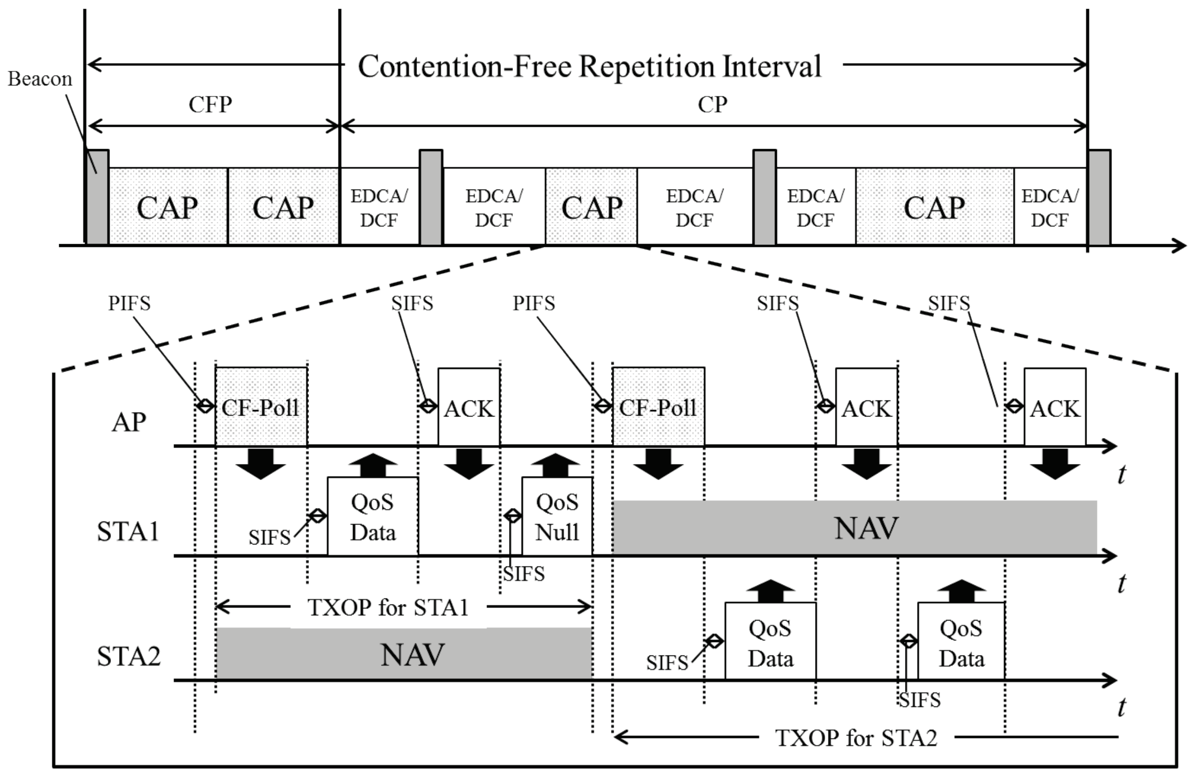

Fig. 2.9 Basic operation of HCCA.

2.2.4. Power Save Multi-Poll (PSMP)

The PSMP is a scheduling function introduced in the IEEE 802.11 to enhance power efficiency for each STA. Each STA can inactivate its WLAN interface during the period when it is not scheduled to transmit or receive by the AP. Therefore, the AP manages the timing of transmission for each STA and STAs use TSPEC mechanism to inform requirement of resources for their QoS data. The basic operation of the PSMP is depicted in Fig. 2.10. In the PSMP, An AP broadcasts a PSMP frame to all STAs. This PSMP frame contains information about the timing of transmission and of reception for STAs. Besides, the PSMP frame indicates the length of Downlink Phase and Uplink Phase. The PSMP procedure enables the AP to divide transmission period into Downlink Phase and Uplink Phase. In Downlink Phase, only the AP can transmit signals to STAs and these STAs are prohibited from sending any signals including ACK frames by setting NAV. On the other hand, each STA can transmit at designated timing during Uplink Phase. In the PSMP sequence, MAC Protocol Data Units (MPDUs) or Aggregate MAC Protocol Data Units (A-MPDUs) are allowed to be used for data transmissions. At this point, the MPDU is a unit of a data frame on the MAC layer, and the A-MPDU consists of multiple MPDUs. Moreover, they are delivered in the interval of SIFS or RIFS. On the other hand, STAs and the AP send an ACK, Block ACK or Multiple Traffic Identifier Block ACK (MTBA) in their transmission period (Downlink Phase for the AP, Uplink Phase for STAs) for data received during prior Downlink Phase or Uplink Phase. A period that consists of Downlink Phase and Uplink Phase is called a PSMP sequence. As a result, STAs only receive or transmit signals during assigned period which is indicated by the PSMP frame.

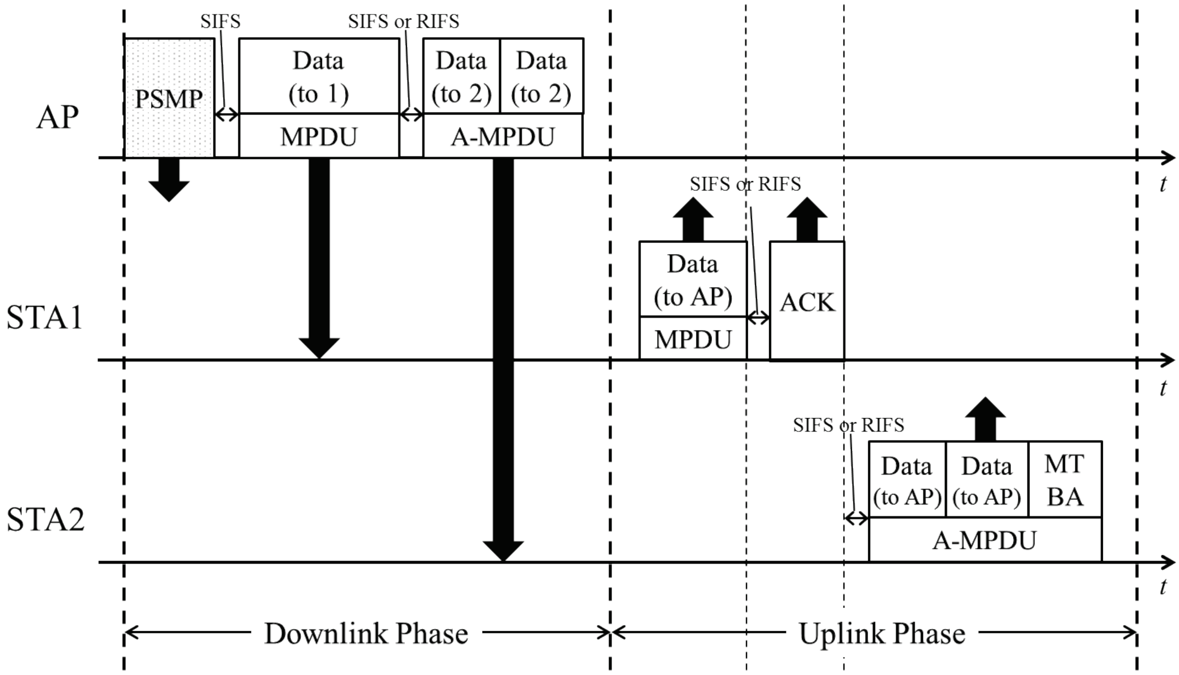

Fig. 2.10 Basic operation of PSMP.

2.3. Issues and Approaches on MAC Protocols for WLAN

As explained in Subsection 2.2, WLAN systems have several types of MAC protocols. Communication systems including WLAN systems are likened to transportation systems. Transmitted data frames are compared to cars as analogy and medium for communication channel is compared to road as well. In the assumption, MAC protocols for communication systems are compared to traffic regulations for transportation systems. In transportation systems, a lot of collisions between cars happen frequently if the traffic regulations are not established and it is difficult to reach the destination without any accident. The same can be said for communication systems. If two or more STAs transmit data frames simultaneously, the transmitted frames collide and interference is generated. This results in transmission failure. Therefore, it is very important to regulate high efficient and flexible MAC protocol that can eliminate collision between transmitted frames.

In wireless systems, a lot of issues are raised in addition to collisions. First, multipath propagation according to the nature of radio signals should be considered. There are reflection, diffraction, and scattering as significant phenomenon of radio signals. According to these factors, the received signal power varies as a function of time. This results in instability in the communications. Although physical layer approaches are mainly key factor to combat this issue, a handshake procedure for confirmation of success of communication in MAC layer perspective is also important. Second, errors of transmitted frames are more likely in wireless systems compared to wired systems as a consequence of the time-varying channel and varying signal strength. The bit error rates are typically less than 10^{-6} in wired systems and the probability of a packet error is small. In contrast, wireless channels may have bit error rates as high as 10^{-3} or higher, resulting in a much higher probability of frame errors in wireless systems. Therefore, the way of retransmission for the failed frame is a key factor to cope with this issue. Last, in the wireless medium, because of radio propagation, signal strength decays according to distance. According to this fact, only STAs within a specific radius of the transmitter can detect the signal on the channel. This causes unintended frame collisions or refrainment for transmissions. This problem of unintended collisions is known as hidden-node problem. Besides, the problem of unintended refrainment is known as exposed-node problem as well.

2.3.1. Studies on MAC Protocols

To enhance the performance of wireless systems and to combat these issues, a lot of prior studies concerning MAC layer including the CSMA/CA have been proposed and improved. Following schemes that have been proposed in the past are typical example of MAC protocols for wireless systems besides the CSMA/CA.

For instance of contention based protocols, Busy Tone Multiple Access (BTMA) that uses an out-of-band busy tone signal to prevent hidden STAs is proposed in Refs. [2.10][2.11]. In BRMA, a busy tone broadcasts the status of the transmitter to STAs in wide range. Although this solution can reduce the number of hidden STAs, the number of exposed STAs is increased in exchange. Furthermore, additional wireless interface that transmits a busy tone is required. Refs. [2.12][2.13] introduce Multiple Access with Collision Avoidance (MACA) that uses RTS-CTS handshake as a solution to the hidden-node problem. In MACA, a STA that has data to send transmits a short Request to Send (RTS) frame before starting a data frame. All STAs that heard the RTS frame defer their transmissions. Then, the receiver of the RTS frame responds with a Clear to Send (CTS) frame to the transmitter of the RTS frame and the period for transmission of the RTS transmitter is ensured. This handshake enables to reduce hidden STAs but overhead time of handshaking is increased in exchange.

Another protocol defined as Idle Sense Multiple Access (ISMA) [2.14] is one of the contention based protocol such as the CSMA/CA, however, an AP coordinates to inform channel condition in this protocol. When the wireless channel is idle, the AP broadcasts an idle signal (IS). If each STA has a data to send, it is transmitted with the certain probability. If the transmission succeeded, the AP broadcasts an IS with Acknowledgment (ISA) which informs the success of the previous transmission with information of idle state for the channel. Improved versions of ISMA are introduced in Refs. [2.15][2.16]. Ref. [2.15] utilizes reservation frames, and Ref. [2.16] introduces timeslot to ISMA.

In contrast to contention based protocols, non-contention based protocols performs good throughput, bounded latency, fairness and user level QoS control because there are no collisions and minimized idle listening if once the schedule is set up. However, it is difficult to estimate actual requirement of frequency resource for each STA or extra handshake procedures for exchanging the requirement are generated in non-contention based protocols. Furthermore, it is hard to cope with flexible topology of network deployment and some sort of synchronization function is also required. Basically, transmission timing for each STA is designated or scheduled by coordinator in almost non-contention based protocols. Time Synchronized Mesh Protocol (TSMP) [2.17] for wireless sensor network systems can be cited as one of the few examples of non-contention based protocol that does not need any coordinator. However, TSMP requires network-wide synchronization to operate instead.

Non-contention based protocols are also introduced in WLAN systems as described in Subsection 2.2. The PCF, HCCA and PSMP are classified into non-contention based protocols. Although these protocols provide some QoS mechanism to WLAN systems because an AP can coordinate each STA's transmission timing, these are rarely used in practical WLAN systems. The reason comes from the fact that it is difficult to synchronize and cooperate between APs as described.

Hybrid of contention based protocol and non-contention based protocol merges the best features of both types of protocol. Packet Reservation Multiple Access (PRMA) [2.18] has scheme of slotted ALOHA reservation but it is operated by scheduling manner. If a STA has a series of data frame to send, The STA tries to reserve for communication in any free timeslot. If it is successfully reserved by the BS, the STA obtains continuous reservation in the corresponding slots of the next frames, until it releases the reservation. The concept of PRMA has been widely used and developed in mobile communication systems.

With diversification and multipurpose usage of wireless systems, many MAC protocols are extensively investigated. Ref. [2.19] organizes and compares classical MAC protocol based on topology of the network. Refs. [2.20][2.21] analyze characteristic features of a lot of protocols for sensor networks. MAC protocols concerning combination with physical layer approach using beamforming are investigated in Ref. [2.22]. Moreover, protocols from the perspective of QoS are given in Ref. [2.23]. Some MAC protocols in these references are focused on controlling a great deal of STAs in sensor networks. However, in sensor networks, each STA has little data to send and the frequency of data transmission is sparse because each STA sleeps almost duration for power saving. Therefore, those protocols are hard to cope with the issues raised in wireless dense environment in WLAN systems. Thus, innovative MAC layer approaches are required to deal with the problems.

2.3.2. Novelty of This Research

Although existing WLAN systems based on the IEEE 802.11 cannot solve the issues raised in wireless dense environment introduced in Subsection 1.4, there are some prior researches aimed at providing solutions for those issues.

Firstly, there are the following approaches as the solutions for co-channel interference caused by frame collisions. Mainstream of these approaches is setting the optimal parameters by using various metrics instead of parameters defined by the IEEE 802.11 standard. Typical criteria for deciding parameters such as IFS, CW and duration of back-off slots are proposed as follows. Loss differentiation of the packet error rate (PER) [2.24], idle time [2.25]-[2.27], transmission rate [2.28], and frame size [2.29] are utilized as those criteria. Besides, game theory is utilized to optimize the CW in Ref. [2.30]. Most of these schemes dynamically change the CW to decrease the possibility of collision. Although these schemes can improve the system throughput, accurate estimation concerning each STA such as frame size, transmission rate, or traffic pattern is needed to set the optimal value for each criterion. Another approach is changing the BEB or modifying the back-off procedure itself. In Ref. [2.31], instead of BEB, a slow decrease scheme is introduced that divides the CW by two instead of resetting it to the initial CW_{min} value after a successful transmission. Ref. [2.32] introduces negative acknowledgement (NAK) frame to distinguish the reason for frame loss caused by transmission or by collision. A procedure in which an AP and STA negotiate with each other for a specified back-off is proposed in Ref. [2.33]. Ref. [2.34] proposes a polling ACK mechanism to permit the designated STA to transmit without performing any contention process. These approaches can cover the disadvantages of the existing CSMA/CA and yield good performance according to their intelligent control. However, modifying the back-off algorithm or back-off procedure has a drastic impact on the implementation and backward compatibility. On the contrary, the proposed scheme introduced in

Chapter 3 can be controlled without accurate estimation of condition of each STA and has high backward compatibility according to its simple operation. Comparison between conventional approaches and the proposed scheme is summarized in Table 2.3.

Secondly, following approaches are proposed for establishing QoS control architecture for each user. In Ref. [2.35], a user-oriented QoS protection method using the EDCA is proposed. The method converts each AC corresponding to a single application into an AC corresponding to a single specified STA. This method utilizes the existing EDCA framework; however, the resulting plethora of queues for the number of STAs significantly increases the implementation costs. Moreover, the method cannot prevent collisions generated between prioritized STAs because of the CSMA/CA operation. Therefore, the method does not prevent throughput degradation, especially in a wireless dense environment. Another approaches proposed in Ref. [2.36]-[2.39] utilize both polling based and contention based control. Ref. [2.36] proposes a polling ACK mechanism to permit the designated STA to transmit without performing any contention process in the DCF. Ref. [2.37] proposes a QoS control method by a priority-based back-off scheme to provide application-oriented QoS. Moreover, the methods in Ref. [3.38] and Ref. [2.39] utilize both fixed back-off and random back-off by sending the back-off timer information together with the data or control frames destined to each given STA. However, it is difficult to maintain polling based control because the AP has to gather each STA's information frequently and schedule the transmission timing for each STA. Moreover, it is also difficult to coexist with legacy STAs because control mechanism is totally different from the CSMA/CA. On the contrary, the proposed scheme introduced in Chapter 4 can establish QoS control architecture for each user without drastic change from CSMA/CA and can coexist with legacy STAs. Moreover, the proposed scheme can improve system performance significantly by utilizing pseudo-centralized operation. Comparison between conventional approaches and the proposed scheme is summarized in Table 2.4.

Finally, approaches for mutual system interference caused by other wireless systems are introduced as follows. Refs. [2.40], [2.41] analyzed the effect of mutual system interference in a heterogeneous network of WLAN, Bluetooth and / or WiMAX in detail, however no interference avoidance technique was introduced. There are a lot of schemes that can suppress interference in the PHY layer [2.42]; however, hardware modification of existing WLAN terminals is required and signal processing is complex when using the interference suppression. A MAC layer approach by which WLAN and WiMAX can coexist [2.43], is introduced in the WiMAX Forum [2.44]. That scheme leverages the sleep mode function specified in the IEEE 802.16e. In this scheme, WLAN AP executes its normal transmission during WiMAX sleeping period, on the other hand, all WLAN devices refrain from transmission during the WiMAX listening period. Although this scheme can prevent mutual system interference, it halves the throughput of each wireless system because each system can utilize only half of period for transmission. On the contrary, the proposed scheme introduced in Chapter 5 can avoid mutual system interference without sharing communication period and realize simultaneous transmission for WLAN and WiMAX. Moreover, the proposed scheme can be easily implemented because it is realized by utilizing MAC function defined in the IEEE 802.11 standard. Comparison between conventional approaches and the proposed scheme is summarized in Table 2.5.

Therefore, techniques proposed in Chapter 3 through 5 have a lot of advantages in various aspect compared with the prior studies. These techniques should open up new vistas in the field of WLAN systems and break the issues raised in the wireless dense environment.

Table 2.3 Comparison of approaches against issue of frame collisions.

Approach \ Requirement	Improvement effect of system performance	Accurate estimation of conition of STAs	Backward Compatibility	Easiness of co-existence with legacy STAs
Parameter optimization	Moderate	Required	Moderate	Moderate
Modification of BEB algorithm	Moderate	Required	Moderate	Difficult
Proposed scheme introduced in Chapter 3	Moderate	Not required	High	Easy

Table 2.4 Comparison of approaches against issue of establishing user-oriented QoS architecture.

Approach \ Requirement	Improvement effect of system performance	Flexibility of QoS control	Backward Compatibility	Easiness of co-existence with legacy STAs
Enhancement of EDCA	None	Low	High	Easy
Utilization of polling mechanism	High	High	Low	Difficult
Proposed scheme introduced in Chapter 4	High	High	Moderate	Easy

Table 2.5 Comparison of approaches against issue of mutual system interference.

Approach \ Requirement	Improvement effect of system performance	Impact on hardware modification	Backward Compatibility	Easiness of co-existence with legacy STAs
PHY layer approaches	High	High	Various	Various
Time division duplex	Low	Moderate	High	Easy
Proposed scheme introduced in Chapter 5	High	Low	High	Moderate

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Chapter 3

Frame Collision Reduction Scheme for Wireless Dense Environment

3. Frame Collision Reduction Scheme for Wireless Dense Environment

3.1. Introduction

As described in Chapter 1, many mobile devices such as smartphones, tablet PCs, gaming machines, and mobile routers, equipped with WLAN interfaces that comply with the IEEE 802.11 standard have rapidly proliferated recently. This proliferation is resulting in an increase in congested situations with many STAs which is defined as a wireless dense environment. The IEEE 802 LAN/MAN Standards Committee (LMSC) established a SG called HEW in May 2013. One of the aims of the HEW SG is to improve the system throughput characteristics for a certain area in wireless dense environments [3.1]. HEW is currently discussing some issues that degrade the system performance in these environments [3.2][3.3]. In particular, the degradation due to a number of frame collisions between STAs is a prominent issue. This problem arises from the mechanism of the CSMA/CA defined as a MAC protocol for the IEEE 802.11. The CSMA/CA is designed in such a way that STAs have to wait for a random back-off time prior to attempting each frame transmission. This random nature of the back-off can reduce the probability of frame collisions between STAs that arises from simultaneous transmission. However, the probability of frame collision increases in proportion to the number of STAs. Therefore, one of the keys to improving the system performance in wireless dense environments is reducing the number of frame collisions between STAs.

Therefore, this chapter proposes a simple MAC protocol based on the CSMA/CA that decreases the number of frame collisions and improves the system performance. No accurate estimation concerning each STA is needed for the proposed scheme. The proposed scheme refrains from any transmission for a certain period if the previous transmission is successful. This period is defined as the Post-Interframe Space (Post-IFS). After a successful transmission, the STA does not participate in the competition for transmission during the Post-IFS, which is the period that other STAs should use. The proposed scheme executes collision-free operation similar to the non-contention based control mechanism if the proposed scheme establishes the optimal value for the Post-IFS. Even if the proposed scheme cannot adjust the optimal value for the Post-IFS, the number of competing STAs and the frame-collision probability can be decreased. This improves the system performance with flexibility. Moreover, an adaptive control scheme for the Post-IFS without accurate estimation is proposed. This accurate estimation includes prediction of frame size, transmission rate, and traffic pattern. In addition, the proposed scheme has little specification impact on the IEEE 802.11 standard.

3.2. Issues of Wireless Dense Environment

There are many issues in wireless dense environments. First, any STA can participate in an unprescribed WLAN network if the STA has information for authentication. Therefore, finite frequency resource is subject to share by all STAs that are connected to the network. Moreover, a number of APs and STAs in the same channel have to share their frequency resource not only with own network but also with overlapping networks because there are many unmanaged APs and STAs in wireless dense environments. Second, an AP broadcasts management frames such as Beacon frame that contains information concerning the WLAN network deployed by the AP. In practical use, the Beacon frames are broadcasted at lowest transmission rate in order to transmit the information to long distance. Moreover, the newer standard comes, the larger the Beacon size become. In fact, the size of the IEEE 802.11n Beacon is approximately from 2 to 2.5 times larger than that of the IEEE 802.11g [3.3]. Therefore, a large number of management frame floods in wireless medium and consumes more wireless channel time. This issue degrades performance of WLAN systems severely. Last, as denoted in Chapter 2, Almost STAs employ the DCF and its basic mechanism of MAC feature is based on the CSMA/CA. However, the default parameters of the IEEE 802.11 standards such as the CW are not optimized for the wireless dense environments. The system throughput versus the CW ratio in saturated condition is shown in Fig. 3.1. The CW ratio is defined as the ratio of CW to the number of STAs and it is represented in Eq. (3.1). Moreover, the saturated conditions indicate the environment that the STAs always had data to send,

$$CWratio = \frac{CW_{\min}}{N}. \tag{3.1}$$

In Eq. (3.1), N denotes the number of STAs in the network. According to the figure, 180 is the number for CW_{min} that maximize the system throughput when the number of STAs is 30. However in the almost IEEE 802.11 standards, the value of CW_{min} is fixed to 15 and this value is independent of the number of STAs. As a result, a great number of collisions is generated and this also degrades performance of WLAN systems seriously.

In consideration of the background, there have been many studies on the IEEE 802.11 WLAN system to reduce the number of collisions. Behavior of the CSMA/CA protocol is modeled and analyzed by using a discrete Markov chain as described in Ref. [3.4]. This reference shows that the system parameters such as the CW, IFS, and the number of STAs strongly influence the system performance. Therefore, as described Subsection 2.3.2, there are many studies to set the optimal parameters by using various metrics [3.5]-[3.10]. Loss differentiation of the packet error rate (PER) [3.5], idle time [3.6]-[3.8], transmission rate [3.9], and frame size [3.10] are utilized to appraise metrics. Ref. [3.11] proposes a novel exploration scheme using game theory to optimize the CW. Most of these schemes dynamically change the CW to decrease the possibility of collision. Although these schemes can improve the system throughput, accurate estimation concerning each STA such as frame size, transmission rate, or traffic pattern is needed to set the optimal value for each criterion.

Another approach is changing the BEB or modifying the back-off procedure itself. In Ref. [3.12], instead of BEB, a slow decrease scheme is introduced that divides the CW by two instead of resetting it to the initial CW_{min} value after a successful transmission. Ref. [3.13] introduces negative acknowledgement (NAK) frame to distinguish the reason for frame loss caused by transmission or by collision. A procedure in which an AP and STA negotiate with each other for a specified back-off is proposed in Ref. [3.14]. Ref. [3.15] proposes a polling ACK mechanism to permit the designated STA to transmit without performing any contention process. These approaches can cover the disadvantages of the existing CSMA/CA and yield good performance according to their intelligent control. However, modifying the back-off algorithm or back-off procedure has a drastic impact on the implementation and backward compatibility.

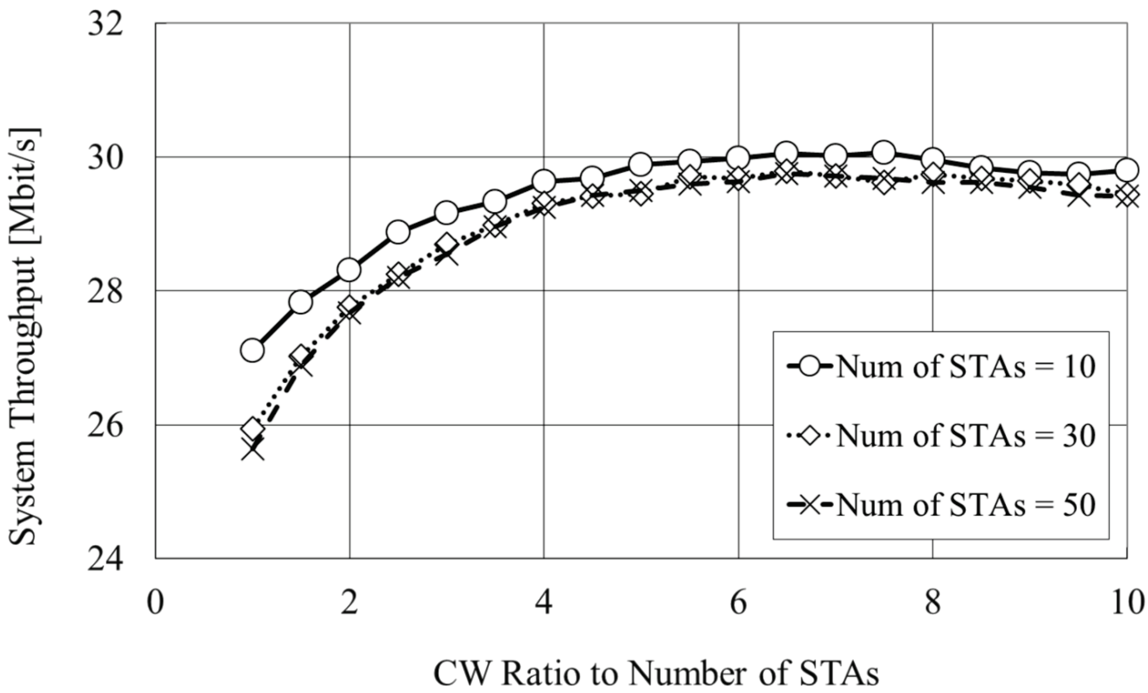

Fig. 3.1 System throughput versus CW ratio.

3.3. Proposed Scheme

In this section, a simple and adaptive frame collision reduction control scheme is proposed. The proposed scheme improves the system performance without drastically changing the existing CSMA/CA. The basic idea is described in Subsection 3.3.1. The procedure to inform the STAs of the length of the Post-IFS is explained in Subsection 3.3.2. The effect of the length of the Post-IFS is discussed in Subsection 3.3.3 and how the length is calculated is proposed in Subsection 3.3.4.

3.3.1. Basic Operation

The basic access mechanism and the flowchart for the proposed scheme are illustrated in Fig. 3.2 and Fig. 3.3, respectively. Although the proposed scheme is based on the CSMA/CA, the significant difference from the CSMA/CA is the existence of time to refrain from transmission, which is defined as Post-IFS. The basic operation of the proposed scheme is described below.

At first, a STA sends a data frame if the wireless channel is idle when the time for waiting for back-off time has expired. If an AP receives the data frame successfully, the AP returns an ACK frame to the STA. This operation is the same as the conventional CSMA/CA. If the STA receives an ACK frame, the STA refrains from transmitting any data frames during Post-IFS whether or not the STA has consecutive frames to send in its transmission queue. This is a unique operation and it can lessen the number of other competing STAs. This results in reduction in the frame collision probability. It takes Fig. 3.4 for instance to describe this operation. Firstly, it is assumed that there are three STAs and these STAs compete for an opportunity for transmission. All these STAs contend with each other in the initial back-off procedure. Secondly, if STA 1 wins the competition, STA 1 performs a data frame exchange with the AP and halts all transmissions during the Post-IFS. The number of competitors is decreased by STA 1 when STAs 2 and 3 compete for an opportunity of transmission. Finally, STA 3 obtains an opportunity of transmission automatically without competing with any other STA if STA 2 wins the previous competition. Although the STA that successfully completed the previous transmission has to forsake the next transmission opportunity during the Post-IFS, the other STAs can utilize the Post-IFS at a lower collision probability. In addition, the system performance does not suffer degradation from the period of the Post-IFS unless no other STA utilizes the channel.

If the STA did not receive an ACK frame due to collision, the STA retransmits its message without waiting for the Post-IFS according to the conventional CSMA/CA procedure as illustrated in Fig. 3.5. This enables the STAs that failed to send a data frame to reduce the overhead time and transmission delay. Moreover, these STA can utilize the idle period of the Post-IFS that is designated for other STAs.

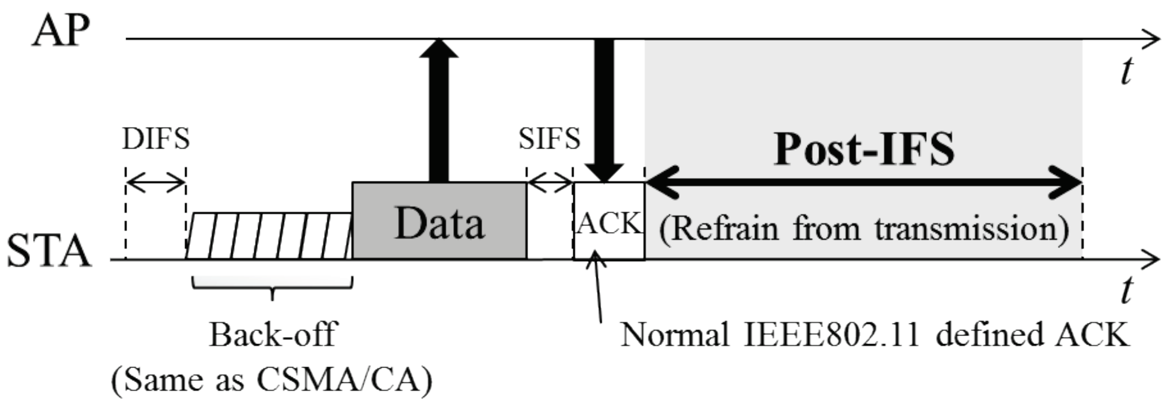

Fig. 3.2 Basic access mechanism of proposed scheme.

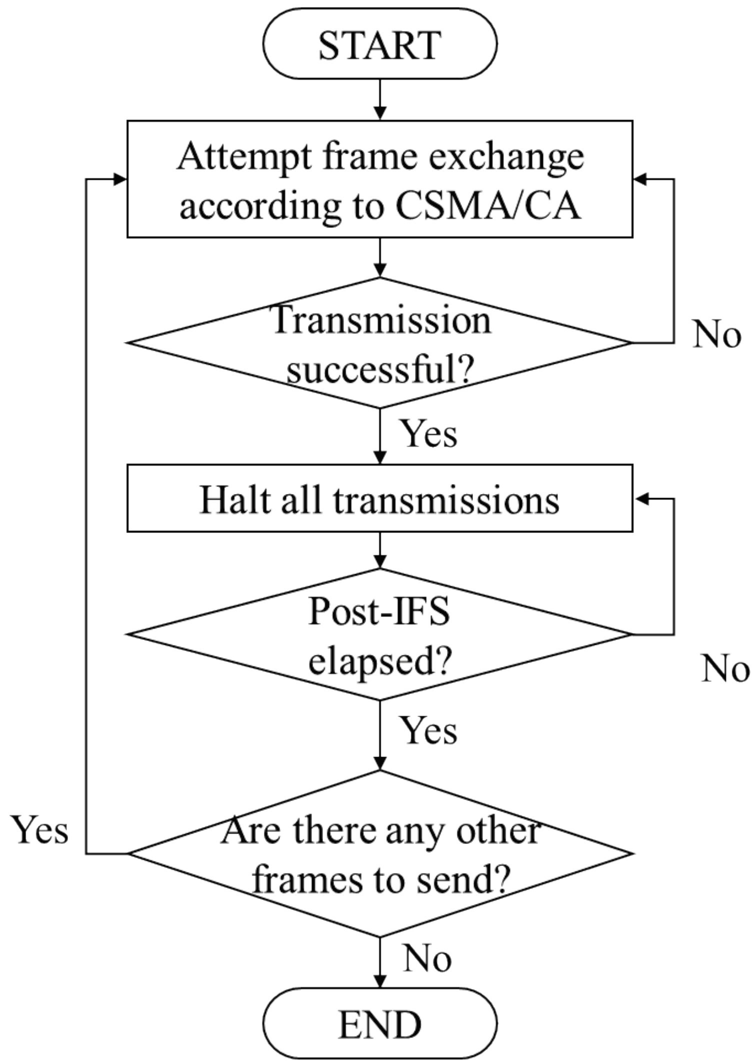

Fig. 3.3 Flowchart of proposed scheme.

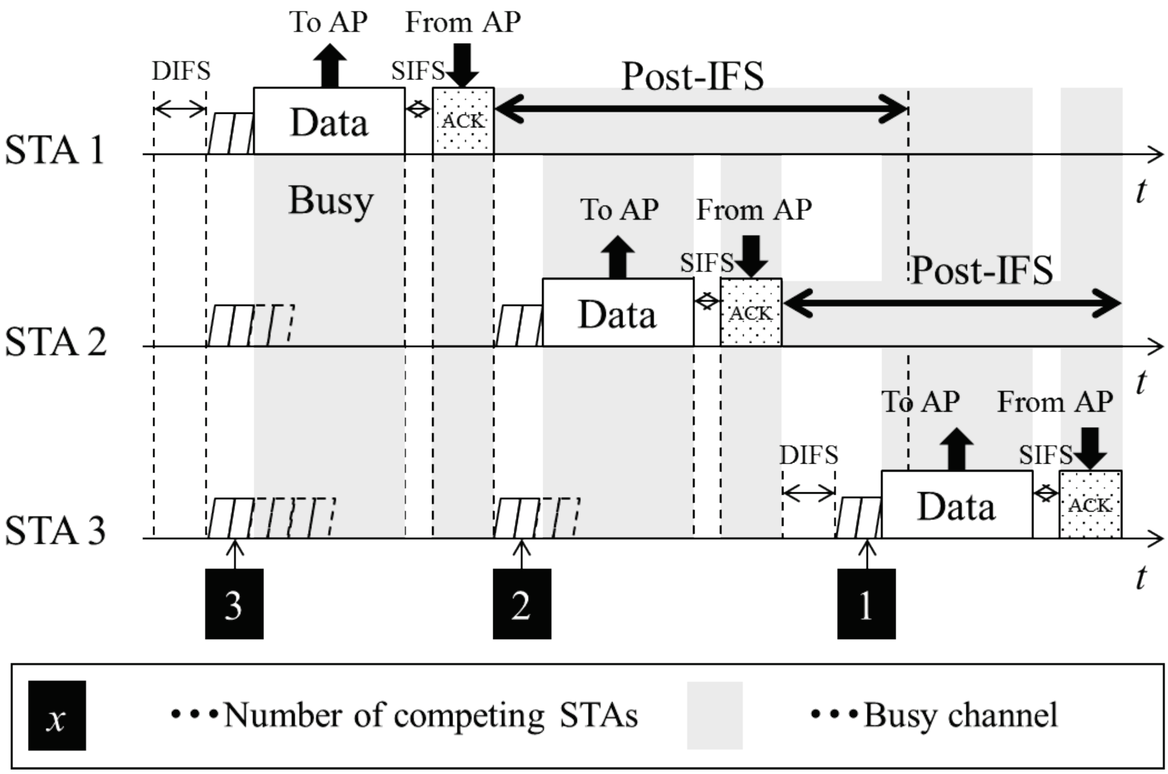

Fig. 3.4 Operation of proposed scheme.

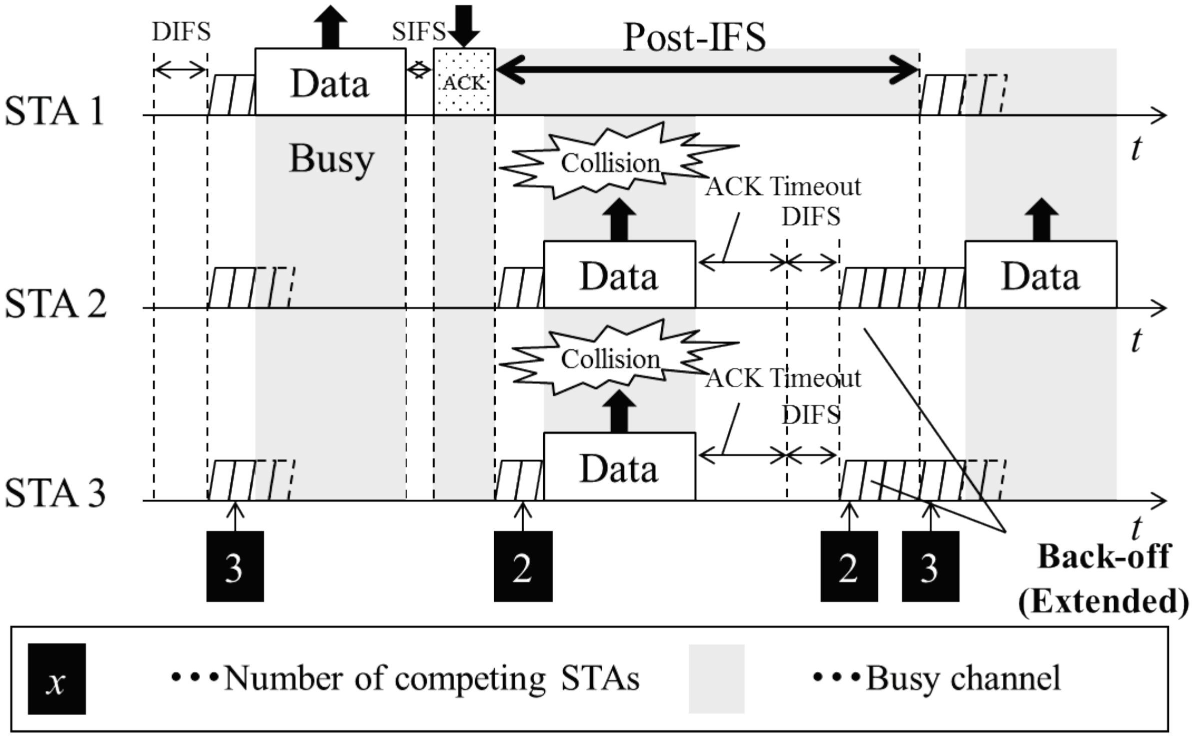

Fig. 3.5 Operation of proposed scheme (collision).

3.3.2. Advertisement of Post-IFS

The procedure for notification and setting of the Post-IFS is described hereafter. Note that how an AP estimates the length of the Post-IFS is explained in Subsection 3.3.4. The STAs are informed of the length of the Post-IFS by using periodic notification such as a beacon frame by an AP. Firstly, the AP attaches the temporal length of the Post-IFS to a beacon frame by describing it in the vendor specific field in the frame. The beacon frame is broadcasted periodically and each STA can apply the Post-IFS according to the information described in the frame. Secondly, the throughput for evaluation is estimated from the multiplication of channel busy rate by the ratio between data and ACK frames that the AP gathered. Finally, the AP modifies the length of the Post-IFS and notifies each STA again. At this point, the AP only needs to set the information for notification of the Post-IFS to the vendor specific field in the beacon frame, and on the STA side, there is no required special implementation except for setting the Post-IFS and refraining from transmission for the period. In addition, no specific frame format needs to be defined. Therefore, the proposed scheme can be achieved with only a slight modification to the CSMA/CA and does not have a large impact on the existing CSMA/CA.

3.3.3. Effect of Post-IFS

In this subsection, the effect of the length of the Post-IFS is discussed. If the optimal value for the Post-IFS is set, the proposed scheme eliminates collisions completely and its operation is performed as a pseudo-centralized control similar to TDMA. This operation is shown in Fig. 3.6. In this case, after STA 4 obtains an opportunity for transmission, the number of STAs that attempts to obtain an opportunity for transmission always becomes one because the other STAs refrain from transmission due to each Post-IFS. Therefore, to actualize this operation, the optimal value for the Post-IFS should be a summation of the time for frame exchange and both the IFS and back-off time periods for each STA except for the STA that sets the Post-IFS. Here it is assumed that N STAs are connected to the AP and an individual STA designation, n (n = 1, 2 … N), is given to each STA. Then it is defined that the period that is needed for a frame exchange by the STA whose STA designation is n as T_n. The period is expressed as follows,

$$T_n = T_{SIFS} + T_{DIFS} + T_{Boff,n} + T_{DATA,n} + T_{ACK,n} \,. \tag{3.2}$$

In Eq. (3.2), T_{SIFS}, T_{DIFS}, and $T_{Boff,n}$ are the length of the SIFS, the length of the DIFS, and the average length of the back-off time for the STA whose STA designation is n, respectively. Terms $T_{DATA,n}$ and $T_{ACK,n}$ represent the times that are taken for transmission of the data frame by the STA and for reception of the ACK frame for the STA, respectively. Therefore, the optimal value of the Post-IFS is expressed as follows.

$$P_n = \sum_{i=1}^{N} T_i - T_n \,, \tag{3.3}$$

where P_n is the length of the Post-IFS for the STA whose STA designation is n. It is necessary to acquire $T_{DATA,i}$ and $T_{ACK,i}$ for all STAs to calculate the optimal value of P_n. Times $T_{DATA,i}$ and $T_{ACK,i}$ are calculated according to the transmission rate and the frame size of the STA including the overhead time for the preamble and frame check sequence (FCS). At this point, it is assumed that S_i is the payload size of the data frame whose STA designation is i and R_i is the transmission rate for sending the data payload. Then, $T_{DATA,i}$, S_i, and R_i have the following relationship,

$$T_{DATA,i} \propto \frac{S_i}{R_i} \,. \tag{3.4}$$

It is difficult to presume S_i and R_i for each STA accurately. However, the proposed scheme can improve the system performance with an incomplete estimation of S_i and R_i in a wireless dense environment in which there are many competing STAs. If P_n is shorter than the optimal value, there still remains a possibility of collision but the probability of collision is reduced due to the Post-IFS. This concept is illustrated in Fig. 3.7. The number of STAs that attempt to obtain a transmission opportunity does not become one when STA 1 tries to obtain the opportunity again. However, the number is reduced by two and the probability of collision is decreased compared to the conventional CSMA/CA. On the other hand, if P_n is longer than the optimal value, extra overhead time is generated but there are no collisions thanks to this long Post-IFS. This concept is shown in Fig. 3.8 as well. The number of STAs that attempts to obtain an opportunity for transmission becomes one when STA 1 tries to obtain an opportunity again. However, the period in which no STA can perform transmission is generated. The degree of improvement in the system performance depends on this trade-off between the reduction in the collision probability and the length of extra overhead.

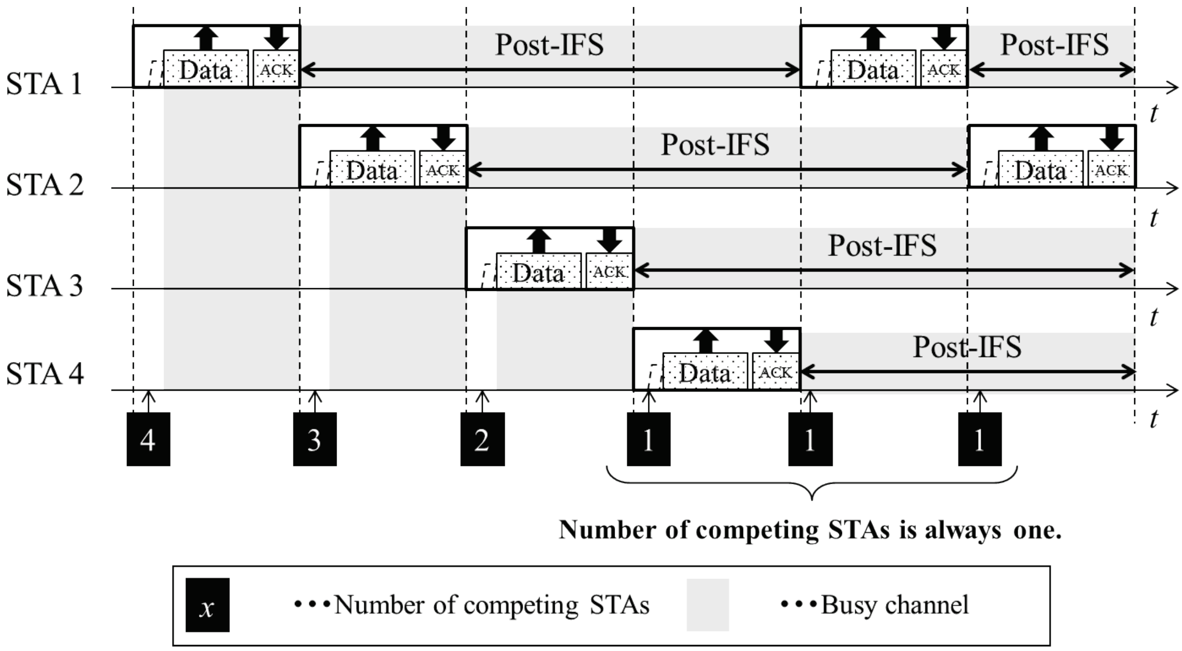

Fig. 3.6 Operation with optimal Post-IFS.

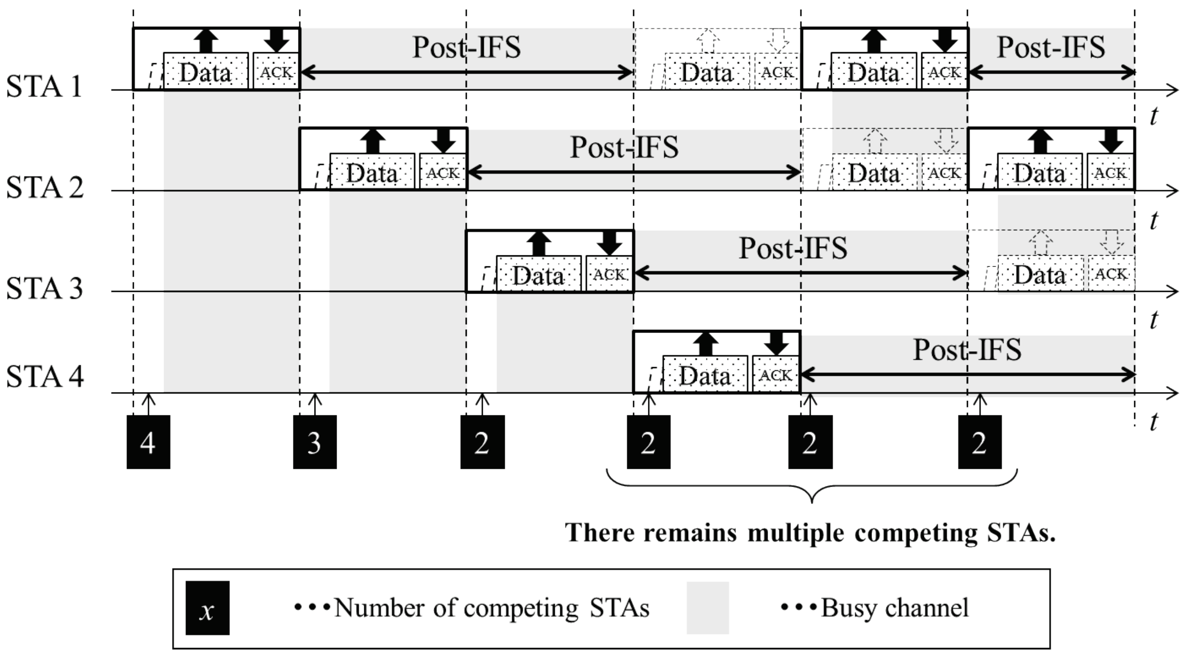

Fig. 3.7 Operation with insufficient Post-IFS.

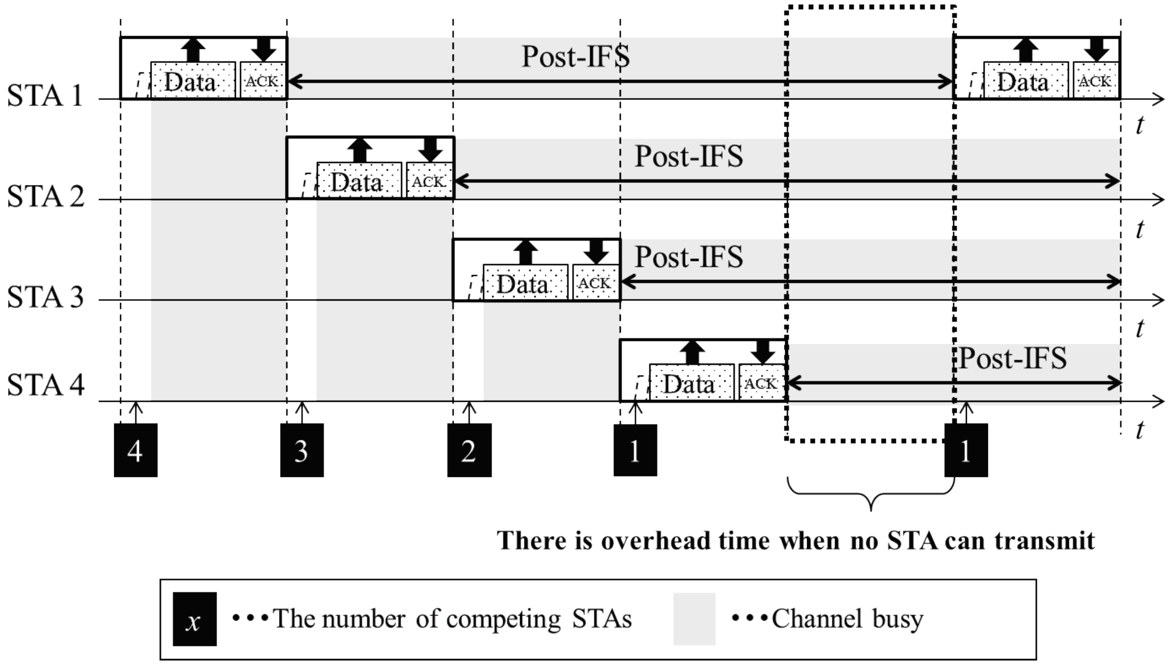

Fig. 3.8 Operation with extra Post-IFS.

3.3.4. Post-IFS Fixed Estimation

First of all, incomplete estimation of the length of the Post-IFS is introduced to facilitate implementation of the proposed scheme. Hereafter, this scheme is defined as the fixed estimation.

In the fixed estimation, it is assumed that common S_{fxd} and R_{fxd} values are used with all STAs for simplicity. Here, S_{fxd} and R_{fxd} represent the specified payload size and the specified transmission rate, respectively. In addition, T_{fxd} is the common value of a period for a frame exchange calculated based on S_{fxd} and R_{fxd}. These S_{fxd} and R_{fxd} values are designated arbitrary or based on observation of transmitted frames. At this point, the average or 50 percentile of the distribution of S_i and R_i can be utilized for the designation. Therefore, the length of the Post-IFS in the fixed estimation is formulated as follows,

$$P_n = (N-1) \times T_{fxd} \,. \tag{3.5}$$

The performance of the proposed scheme with the fixed estimation is evaluated in Subsection 3.4 based on computer simulations and experiments.

3.3.5. Post-IFS Adaptive Estimation

In this subsection, another scheme for estimation that is adaptively controlled and more accurate than the fixed estimation scheme is proposed. This scheme is defined as the adaptive estimation.

The throughput obtained at each STA or the entire system is related to the length of P_n. In other words, the throughput characteristic is a function of the Post-IFS. This adaptive estimation is based on the idea of the steepest decent method [3.16]. Therefore, the length of the Post-IFS changes iteratively according to different throughput characteristics. In the adaptive estimation, the average throughput for evaluation of each STA or the entire system for a certain period is utilized for the criterion. A beacon period is suitable for the period and the Post-IFS is modified for each period. Hereafter, x represents the number of iterations for changing P_n, and $P_n\ (x)$ denotes the length of the Post-IFS at iteration x.

At the first stage, the temporal value of $P_n\ (0)$ is decided based on $S_i\ (0)$ and $R_i\ (0)$. These $S_i\ (0)$ and $R_i\ (0)$ are estimated according to the fixed estimation. Then, the throughput defined as $F\ (0)$ for the period is observed. In the next iteration, an arbitrary value of $S_i\ (1)$ is decided as well as the case for $S_i\ (0)$ to calculate different $P_n\ (1)$ where $S_i\ (1)$ must not be the same as $S_i\ (0)$. Subsequently, throughput for evaluation $F\ (1)$ is observed by using the setting of $P_n\ (1)$. The difference between $S_i\ (0)$ and $S_i\ (1)$ affects the granularity of the exploration for the optimal $P_n\ (x)$. It is defined that this difference as I_{init} expressed in Eq. (3.6),

$$I_{init} = S_i(0) - S_i(1)\,. \tag{3.6}$$

The differentiation of the throughput at iteration x is also defined as follows,

$$\Delta F(x) = F(x) - F(x-1)\,. \tag{3.7}$$

This I_{init} has an impact on ΔF (0) and ΔF (0) affects the granularity of the exploration of P_n (x).

After the iteration, the length of the Post-IFS P_n (x) is decided according to the formula shown in (3.8),

$$P_n(x+1) = P_n(x) - \alpha(x) \times \Delta F(x)\,. \tag{3.8}$$

In Eq. (3.8), α (x) represents the coefficient step-size that decides the ratio of the numerical value updated by iteration. At this point, the STAs or the AP does not know the characteristics of the evaluation function corresponding to the length of the Post-IFS. In other words, the characteristics of the evaluation function are not given to each STA. Moreover, this evaluation function changes momentarily because the throughput characteristics that are the criteria for the function depend on the transmission results of each STA. Therefore, it is facilitated that the forced convergence of the length of the Post-IFS formulated as Eqs. (3.9) and (3.10) to avoid divergence.

If ΔF (x) < 0 and ΔF (x-1) > 0,

$$\alpha(x+1) = \frac{1}{2}\alpha(x)\,. \tag{3.9}$$

Otherwise,

$$\alpha(x+1) = \alpha(x)\,. \tag{3.10}$$

Therefore, the length of the Post-IFS P_n (x) is determined adaptively according to the throughput characteristic. The performance of the proposed scheme with adaptive estimation is also verified in Subsection 3.4.

3.4. Performance Evaluation

To clarify the performance of the proposed scheme, computer simulations are conducted. Firstly, the maximum performance of the proposed scheme and the conventional CSMA/CA are evaluated. Secondly, the proposed scheme with the fixed estimation is evaluated under the condition that S_i cannot be accurately assumed. Finally, the proposed scheme with the adaptive estimation under the same conditions as the fixed estimation is verified. The simulation parameters are given in Table 3.1. Parameters such as the IFS and slot time comply with the IEEE 802.11g. Moreover, these simulations are performed under both saturated and non-saturated conditions. As mentioned in Subsection 3.2, the saturated conditions indicate the environment that the STAs always had data to send. In addition, these simulations are executed with the simulation time of 20 s. The results of these simulations are derived from the mean value of that period. Moreover, it is assumed that the estimation of throughput for evaluation at the AP side is performed completely. Besides, it is also assumed that there are no hidden STAs in the network because this dissertation focuses on clarification of fundamental performance of the proposed scheme.

In addition to those simulation evaluations, experimental evaluations are conducted in order to verify the effectiveness of the proposed scheme under an actual environment. The experimental parameters and the configuration of the experiments are given in Table 3.2 and Fig. 3.9 respectively. Besides, snapshots of a hardware device used for the experiments and of configuration of the experiments are shown in Fig. 3.10 and Fig. 3.11 respectively. The hardware device has the function of an AP and a STA and it can be used for both type of WLAN terminals. Moreover, implementation of Post-IFS achieves only by the WLAN driver's modification, and does not need the modification of hardware. The Post-IFS can be set in 0.067 μs.

Firstly, the effect of the length of the Post-IFS is evaluated as the system throughput characteristic. Secondly, the maximum performance of the proposed scheme and the conventional CSMA/CA under actual environment are evaluated. In these experiments, the system throughput characteristics to the number of STAs are observed. Finally, the system throughput characteristics to the offered traffic load of the proposed scheme and the conventional CSMA/CA are evaluated.

Table 3.1 Simulation parameters.

Evaluation	1		2		3
Condition	Saturated	Non-saturated	Saturated	Non-saturated	Saturated
Number of STAs N	1-50	50	1-50	50	50
Offered Traffic Load [Mbit/s]	50	0-50	34	0-34	34
Data Payload S_i [byte]	1500		500-1500		500-1500
Transmission Rate R_i [Mbit/s]	54		54		54
Maximum Retry	6		6		6
SIFS [μs]	16		16		16
DIFS [μs]	34		34		34
SlotTime [μs]	9		9		9
CW_{min}	15		15		15
CW_{max}	1023		1023		1023
Stepsize $\alpha(0)$ (Proposed only)					0.001
Update Interval for Post-IFS [ms] (Proposed only)					100
Estimated Data Payload S_{fxd} (Proposed only)	1500		100 / 500 / 1000 / 1500		Variable
Initial Differentiation I_{init} (Proposed only)	None		None		100 / 300 / 500

Table 3.2 Experimental parameters.

Experiment	Experiment 1	Experiment 2	
		Saturated	Non-Saturated
Number of APs	1	1	
Number of STAs N	19	1-19	19
Offered Traffic Load [Mbit/s]	34	34	0-50
Data Payload S_i [byte]	1470	1470	
Transmission Rate R_i (Data) [Mbit/s]	54 (Fixed)	54 (Fixed)	
Transmission Rate (Ack) [Mbit/s]	24 (Fixed)	24 (Fixed)	
Maximum Retry	6	6	
Length of Post-IFS (Proposed Only) [μs]	0-10000	According to Eq.(3.5)	
IFS Parameters	IEEE 802.11g	IEEE 802.11g	
Auto Rate Fallback	None	None	
Measurement Tool	Iperf 2.0.5	Iperf 2.0.5	
Protocol	UDP	UDP	
Direction	Uplink	Uplink	
Measurment Time [s]	90	90	

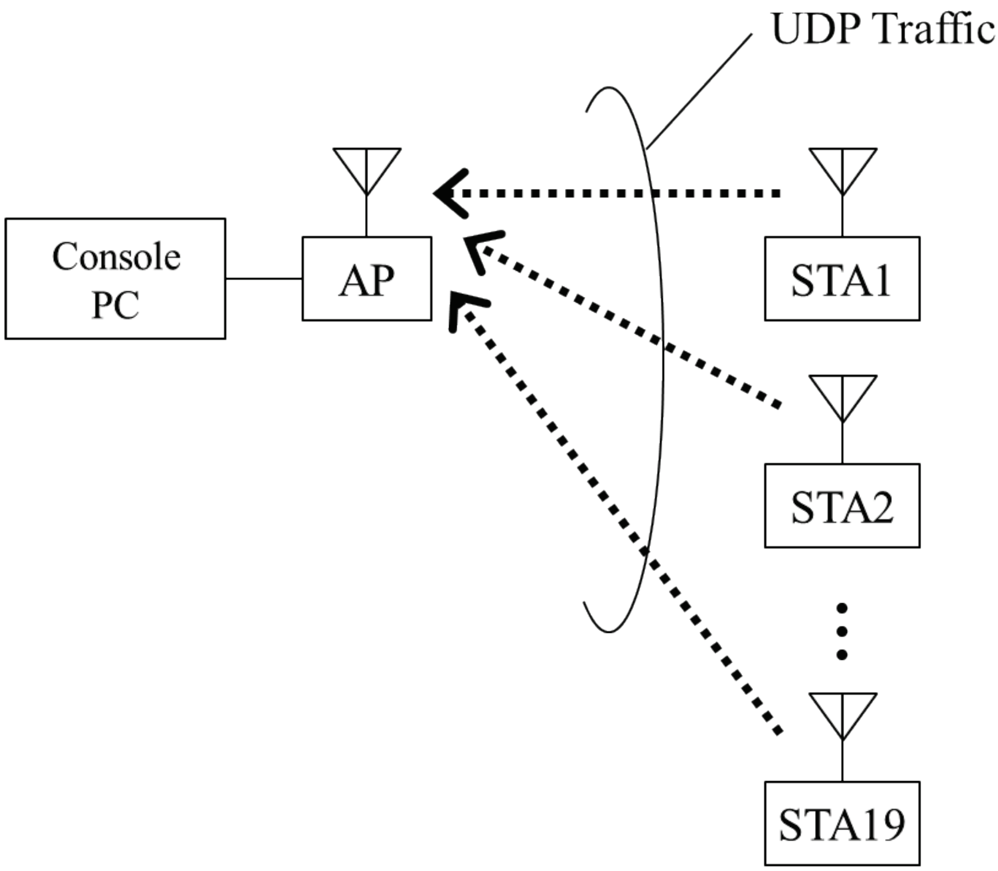

Fig. 3.9 Configuration of experiments.

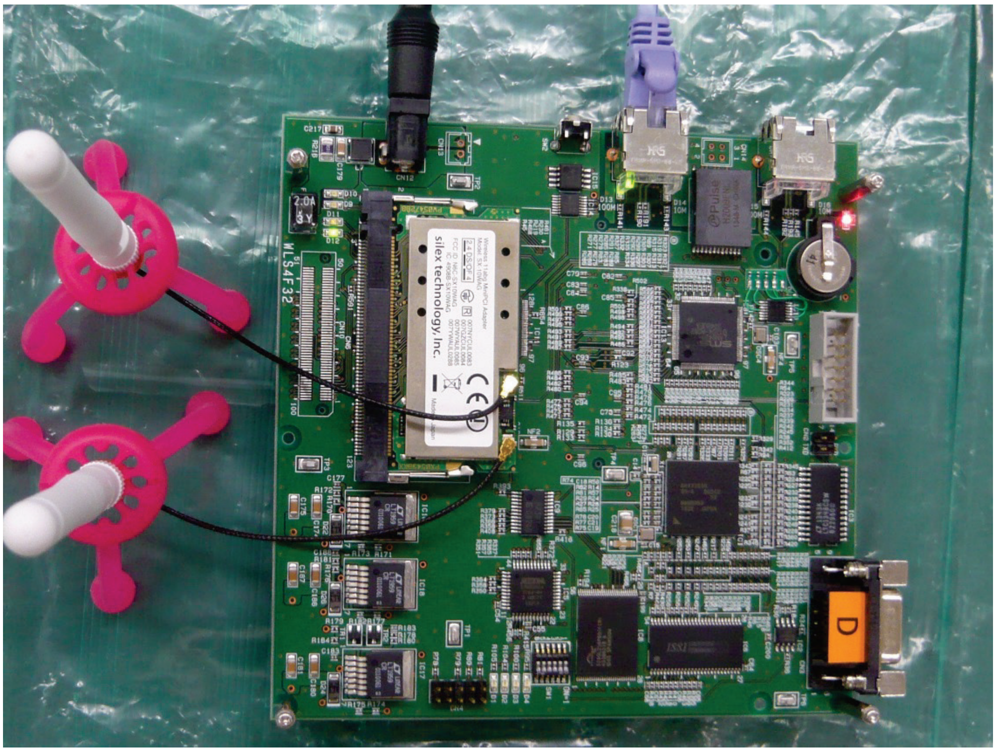

Fig. 3.10 Hardware emulator device.

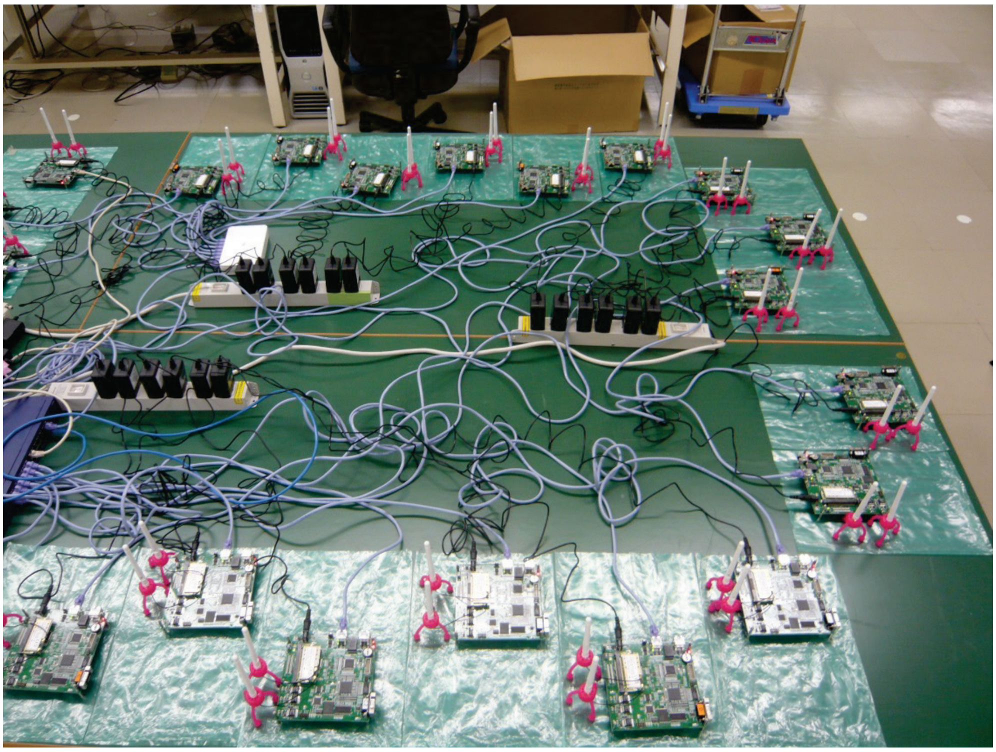

Fig. 3.11 Condition of network configuration.

3.4.1. Simulation 1: Maximum Performance

The evaluation of the system throughput, average access delay and average number of retransmission versus the number of STAs are discussed in this Subsection. Here, the access delay is defined as the period that is counted from beginning of DIFS to completion of an ACK frame reception. In addition, the system throughput versus the number of STAs is discussed in this subsection. The system throughput represents the total throughput of N STAs. In this evaluation, it is assumed that the payload size of data frames S_i and transmission rate R_i are constant and the size is 1500 bytes based on the maximum size of an Ethernet frame. Moreover, it is assumed that the estimation of S_i and R_i are perfect at each STA.

The simulation results under saturated conditions are shown in Fig. 3.12 through Fig. 3.14. The proposed scheme improves the system throughput compared to the conventional CSMA/CA when the number of STAs is equal to or greater than five. This is because the proposed scheme avoids all collisions and performs pseudo-centralized control. Moreover, there is no extra overhead time in the proposed scheme because the optimal value of the Post-IFS is set for each STA. In Fig. 3.12, the proposed scheme achieves 40% higher throughput than that for the conventional CSMA/CA when N is 50.

On the other hand, the conventional CSMA/CA is superior to the proposed scheme when the number of STAs is less than five. This phenomenon stems from the following reason. In the conventional CSMA/CA, the back-off time to compete for obtaining a transmission opportunity is shared among all STAs. In contrast, the back-off time per user is considered to calculate the length of the Post-IFS in the proposed scheme. Therefore, the effect of the extra waiting time of the back-off time for each STA is greater than the effect of the collision reduction in this situation.

As shown in Fig. 3.13 and Fig. 3.14, the proposed scheme reduces the average access delay and the number of retransmissions to approximately 0 regardless of N. These results confirm the effect of collision reduction due to pseudo-centralized control.

Next, these characteristics under non-saturation conditions are evaluated. In these evaluations, frames to send are generated periodically according to a Poisson distribution and the number of STAs is set to 50. The system throughput, average access delay, and average number of retransmissions versus the offered traffic load are evaluated. Fig. 3.15 through Fig. 3.17 shows these simulation results. According to the results shown in Fig. 3.15, the proposed scheme and the conventional CSMA/CA achieve the same throughput when the offered traffic load is less than 25. When the offered traffic load exceeds 25, the traffic flow becomes saturated and the proposed scheme achieves higher throughput than the conventional CSMA/CA. Despite the existence of the Post-IFS, the reasons why the proposed scheme can obtain throughput equal to the conventional CSMA/CA under non-saturated conditions are explained as follows. Firstly, as explained in Subsection 3.1, the waiting time of the Post-IFS does not degrade the system performance if the other STAs utilize the waiting time for transmission. Secondly, if there are no frames to send during the Post-IFS, this wait time does not miss an opportunity for transmission because there is no request to send in the first place. Finally, in a wireless dense environment, the possibility is high that many STAs perform transmissions even if the requests for transmission from each STA are sporadic.

The simulation results of the average access delay and the number of retransmissions are approximately 0 at any offered traffic load because the collisions are eliminated according to the results in Fig. 3.16 and Fig. 3.17. On the other hand, the characteristics of the conventional CSMA/CA worsen due to chronic collision after the offered traffic load exceeds 30.

Therefore, the proposed scheme improves the system performance compared to the conventional CSMA/CA by reducing the number of collisions.

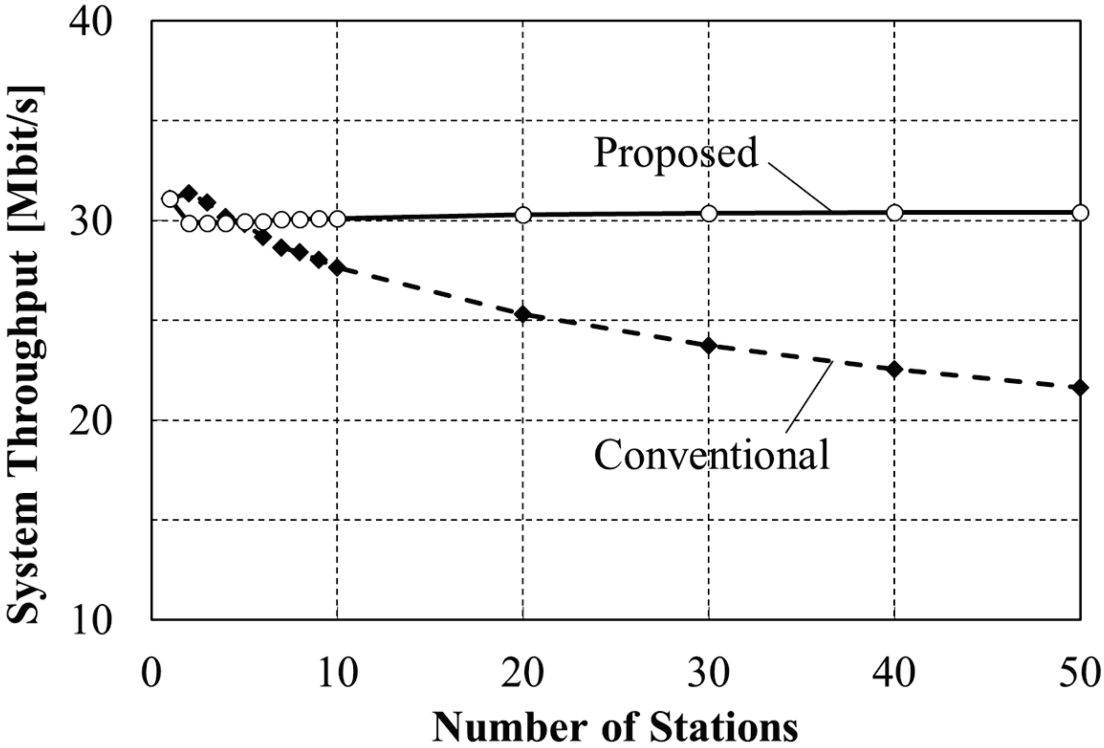

Fig. 3.12 System throughput vs. number of STAs (w/ perfect estimation).

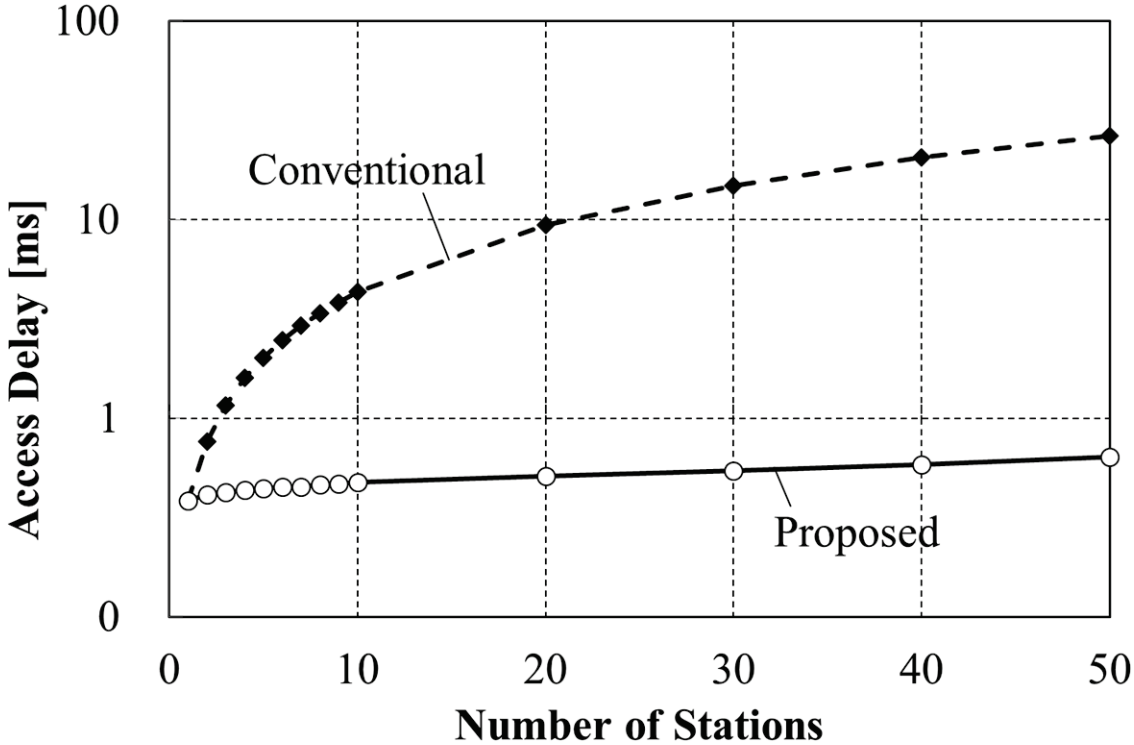

Fig. 3.13 Access delay vs. number of STAs (w/ perfect estimation).

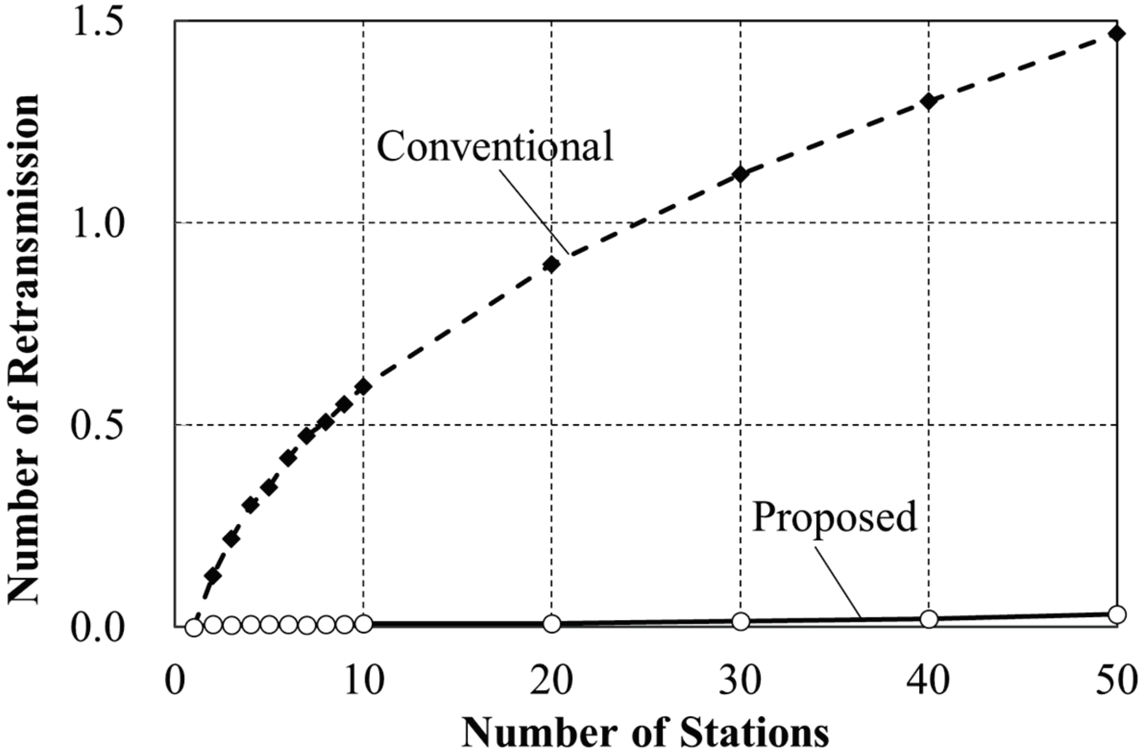

Fig. 3.14 Number of retransmissions vs. number of STAs (w/ perfect estimation).

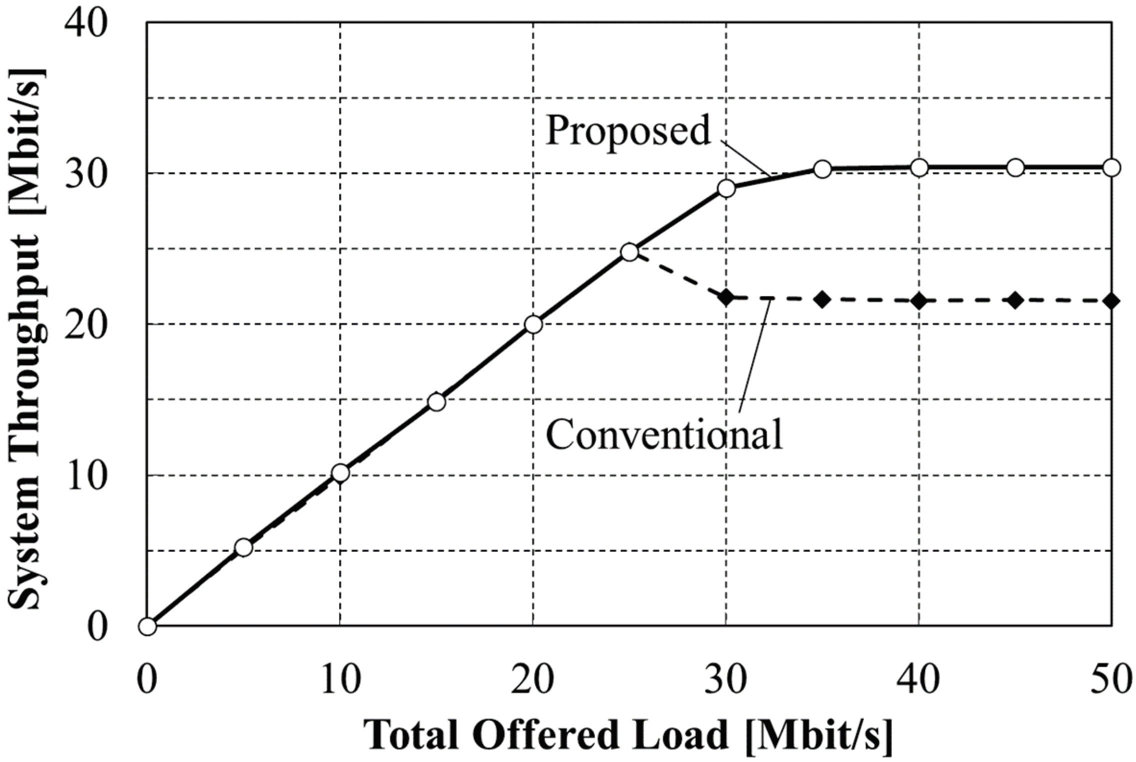

Fig. 3.15 System throughput vs. offered traffic load (w/ perfect estimation).

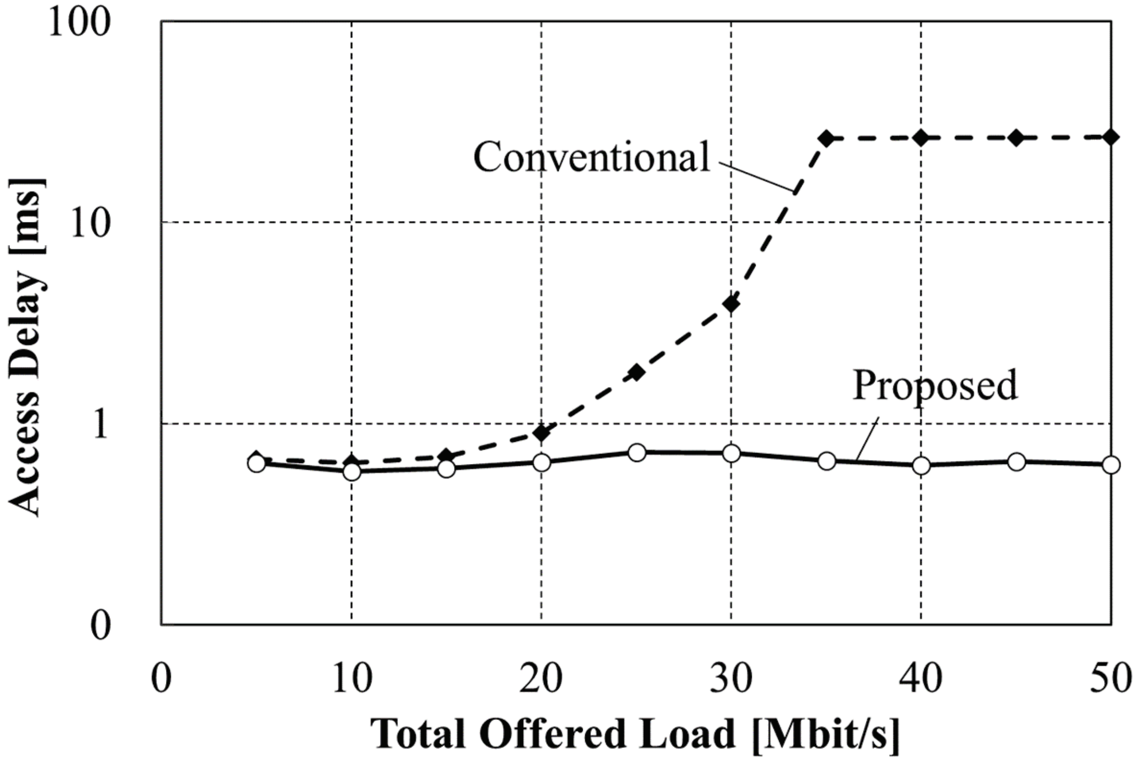

Fig. 3.16 Access delay vs. offered traffic load (w/ perfect estimation).

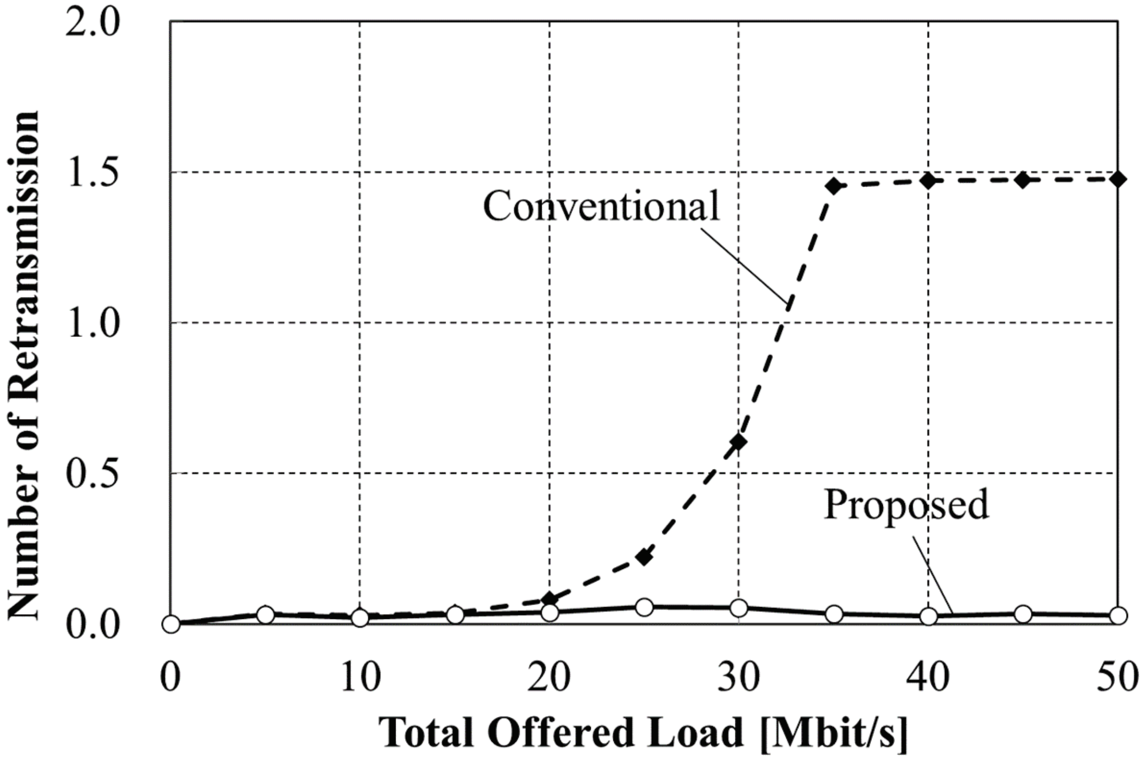

Fig. 3.17 Number of retransmission vs. offered traffic load (w/ perfect estimation).

3.4.2. Simulation 2: Performance with Fixed Estimation

To verify the performance of the proposed scheme with the fixed estimation, it is introduced that a condition in which the AP cannot acquire information regarding the payload size of the data frames of each STA. In this evaluation, it is assumed that the transmission rate is constant but the payload size of the data frames is randomly varied from 500 bytes to 1500 bytes. Under this condition, the proposed STA arbitrarily estimates the payload size as fixed value S_{fxd} and calculates the length of the Post-IFS, P_n, with the fixed estimation. The system throughput and average access delay versus the number of STAs are verified based on comparison to those of the conventional CSMA/CA.

The simulation results concerning the system throughput under saturated conditions is shown in Fig. 3.18. According to the result, in the proposed scheme where S_{fxd} is 1000 and 1500, the system throughput is decreased when the number of STAs is 2. Beyond that it becomes nearly constant regardless of N. On the other hand, the tendency for the system throughput is similar to that for the conventional CSMA/CA when S_{fxd} is 100 and 500 in the proposed scheme. In this case, the system throughput increases relative to the number of STAs at first, then it decreases in proportion to the number of STAs after it reaches the peak value. There is a specific number of STAs where the proposed scheme achieves better throughput than the conventional CSMA/CA in every setting of S_{fxd}. The proposed scheme is superior to the conventional CSMA/CA if the number of STAs is greater than a specific number, i.e., 30, 7, 4 and 3 when S_{fxd} is 1500, 1000, 500, and 100, respectively. The extra overhead of the Post-IFS is considered as a reason why the system throughput of the proposed scheme with a large set value for S_{fxd} decreases where there are only a few STAs. In other words, the payload size of the data frames is varied from 500 to 1500 and its average is 1000. Therefore, if the set of S_{fxd} exceeds 1000, extra overhead time is generated during which no STA can transmit data frames despite the existence of an opportunity for transmission as described in Subsection 3.3.

On the other hand, the reason why the system throughput of the proposed scheme with the set of lower S_{fxd} decreases in proportion to the number of STAs after it reaches the peak value is a number of collisions. As described in Subsection 3.3, the collision probability depends on the length of the Post-IFS and the number of STAs. However, in the case where the proposed scheme employs the value of 100 for S_{fxd} and the number of STAs is greater than 3, the system throughput characteristic of the proposed scheme is superior to the conventional CSMA/CA. In particular, the system throughput is improved by 17% when the number of STAs is 50 despite the great difference between the estimation and the real value. Moreover, the system throughput of the proposed scheme whose S_{fxd} is 1000 is 40% higher than that for the conventional CSMA/CA when the number of STAs is 50.

The simulation results of the average access delay and the number of retransmissions are shown in Fig. 3.19 and Fig. 3.20 respectively. According to the results, the average access delay and the number of retransmissions are suppressed to below 1 in the case where the S_{fxd} values are 1000 and 1500 in the proposed scheme. This confirms the effect of collision reduction due to pseudo-centralized control. On the other hand, in the case where the S_{fxd} values are 100 and 500 in the proposed scheme, those characteristics are degraded in proportion to the number of STAs. However, these characteristics are superior to the conventional CSMA/CA thanks to the effect of the reduction in the number of collisions.

Next, these characteristics under non-saturated conditions are evaluated. Frames are generated based on a Poisson distribution in the same way as in the evaluation described in Subsection 3.4.1. The system throughput, average access delay and the number of retransmissions versus the offered traffic load are evaluated. These simulation results are shown in Fig. 3.21 through Fig. 3.23. According to the results, the operation of the proposed scheme with a longer Post-IFS becomes closer to that for pseudo-centralized control although there is an increase in the extra overhead time. Moreover, it becomes closer to the conventional CSMA/CA if a shorter Post-IFS is applied. The reasons why the proposed scheme can obtain throughput equal to the conventional CSMA/CA under non-saturated conditions are the same as those given in Subsection 3.4.1. Therefore, the proposed scheme improves the system performance in the case where each STA cannot estimate the payload size of the data frames accurately.

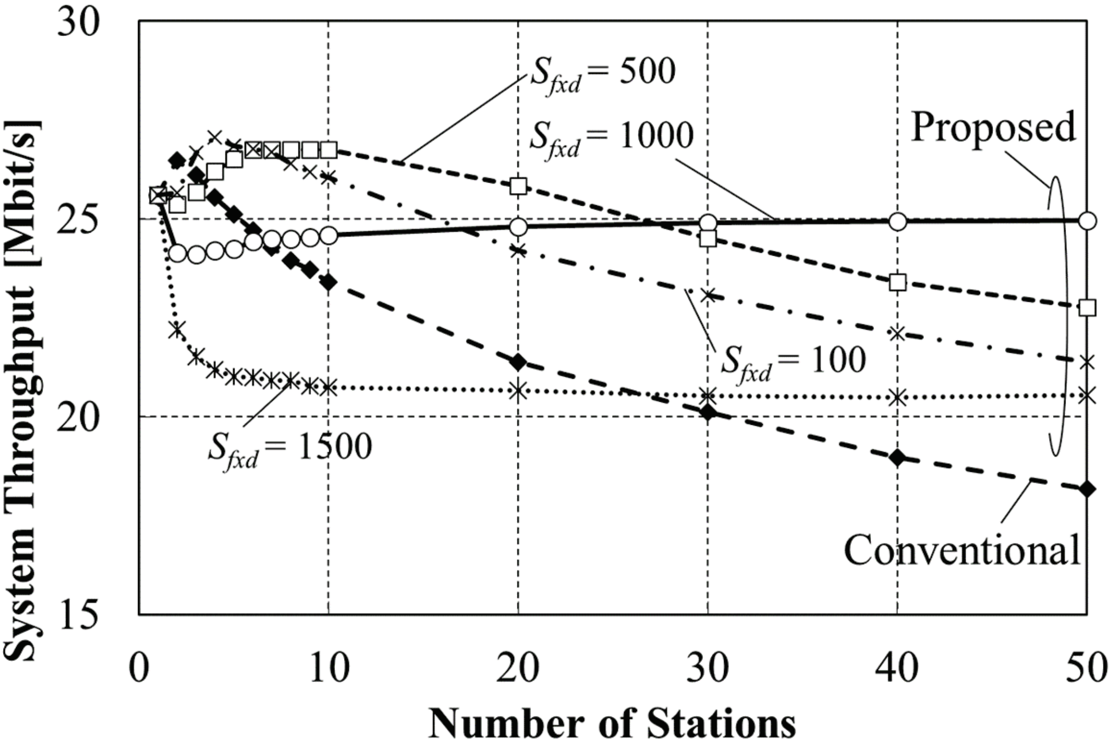

Fig. 3.18 System throughput vs. number of STAs (w/ imperfect estimation).

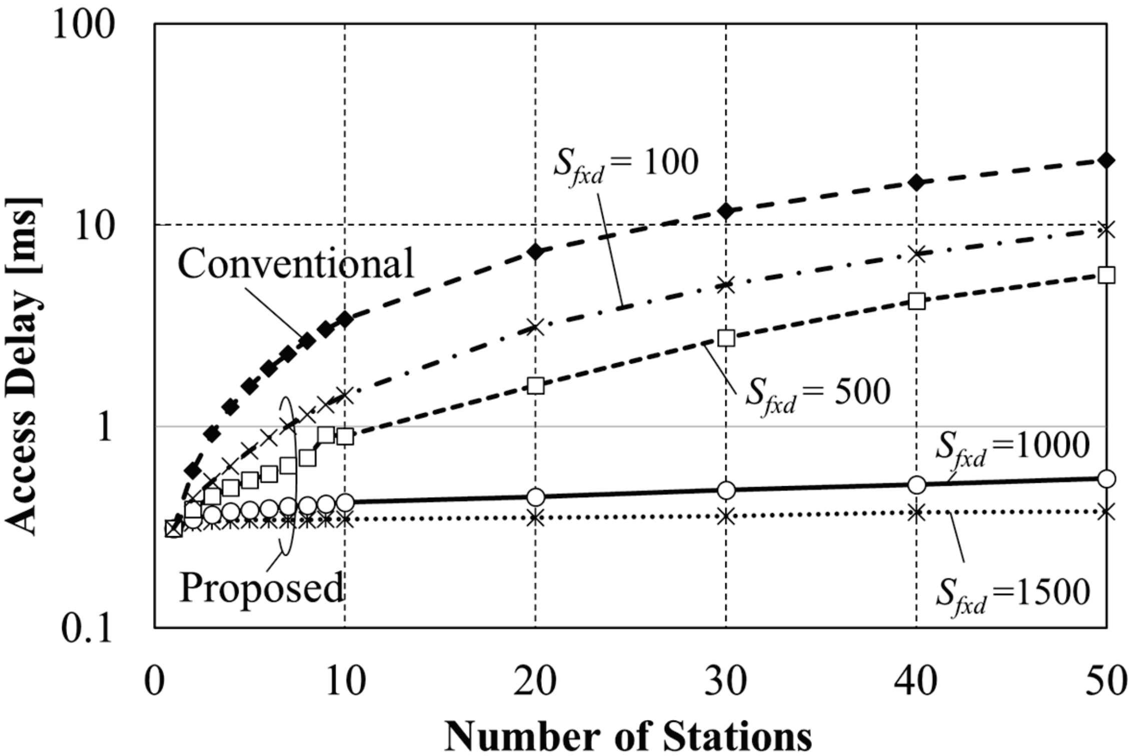

Fig. 3.19 Access delay vs. number of STAs (w/ imperfect estimation).

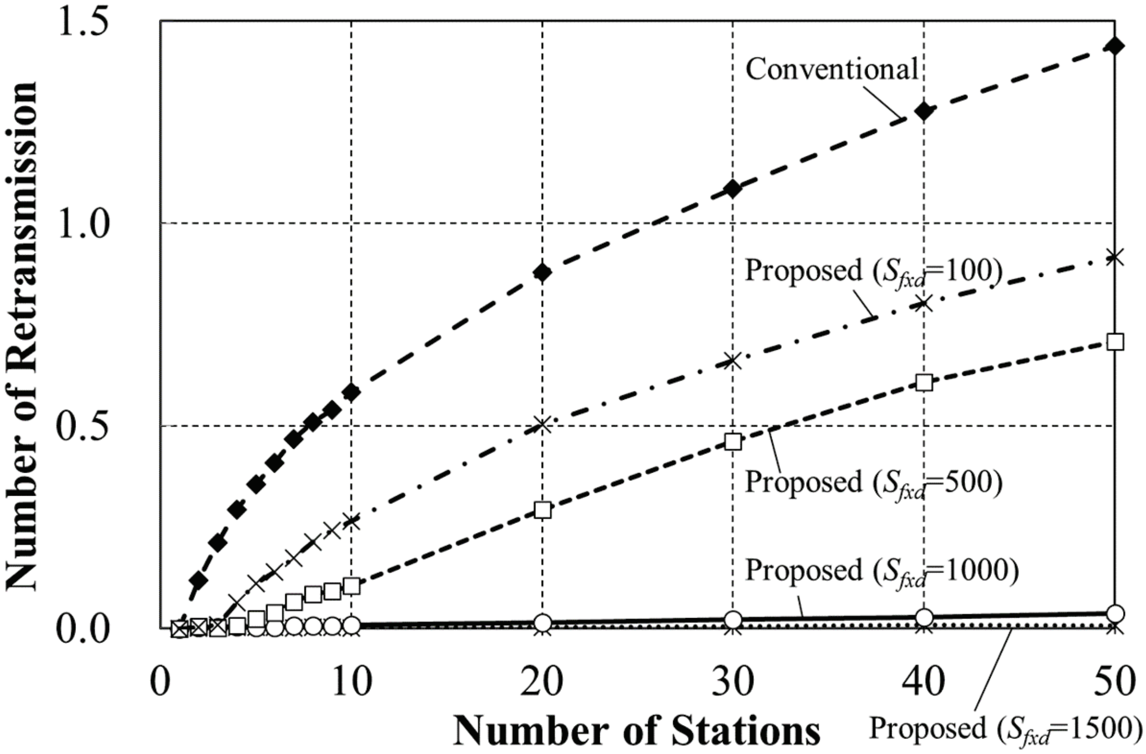

Fig. 3.20 Number of retransmission vs. number of STAs (w/ imperfect estimation).

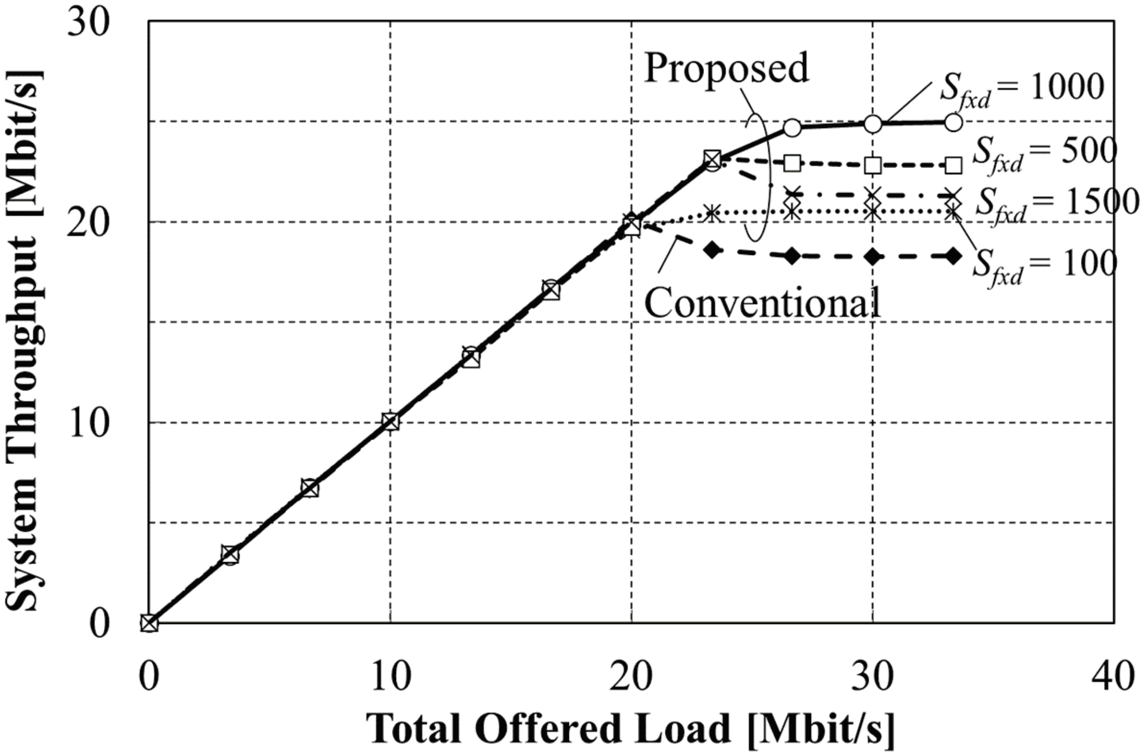

Fig. 3.21 System throughput vs. offered traffic load (w/ imperfect estimation).

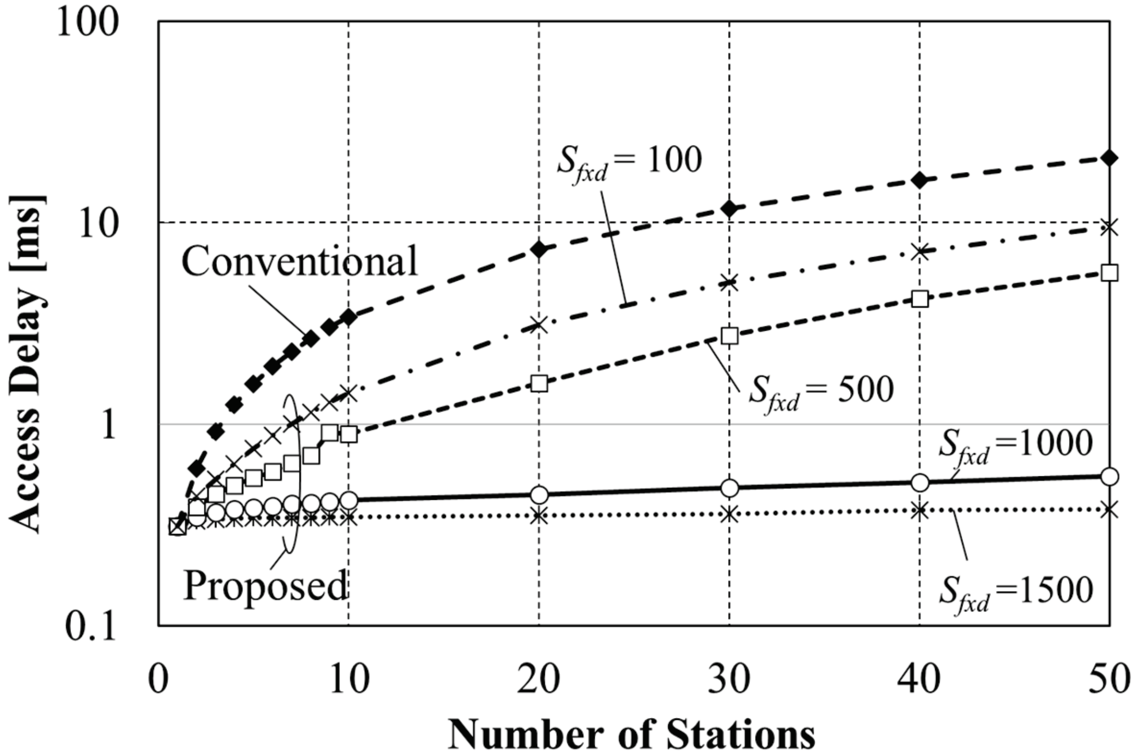

Fig. 3.22 Access delay vs. offered traffic load (w/ imperfect estimation).

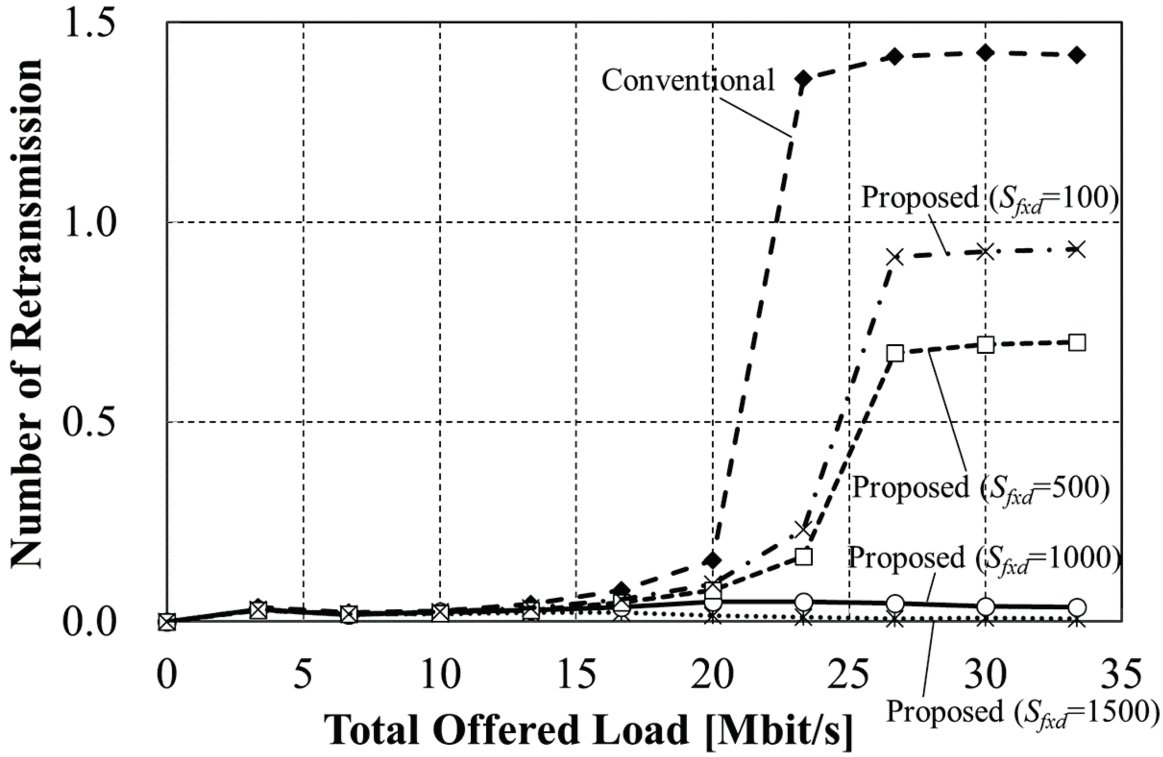

Fig. 3.23 Number of retransmission vs. offered traffic load (w/ imperfect estimation).

3.4.3. Simulation 3: Performance with Adaptive Estimation

In this subsection, the effect of the adaptive estimation is evaluated. According to Subsection 3.3.5, S_i (0) is initially set arbitrarily by using the fixed estimation. Therefore, it is set as follows based on the maximum size of an Ethernet frame,

$$S_i(0) = 1500 \,. \tag{3.11}$$

In addition, it is assumed that the beacon period of 100 ms is utilized as an update interval for iteration. Three kinds of arbitrary differentiations, I_{init}, are evaluated here. Similar to the evaluation in Subsection 3.4.2, it is assumed that the transmission rate is constant but the payload size of the data frames is randomly varied from 500 bytes to 1500 bytes and the AP cannot obtain information regarding the size of each STA. Under these conditions, the system throughput and the length of the Post-IFS, P_n (x), against the number of iterations, x are evaluated. The simulation results of the system throughput and the value of the Post-IFS are shown in Fig. 3.24 and Fig. 3.25, respectively. In Fig. 3.24, the straight line denoted as "ideal" indicates the performance of the case where all STAs perform frame exchange without any collision and any retransmission. According to the results, the proposed scheme of each initial I_{init} cannot obtain sufficient throughput due to the great difference in parameters because of inaccurate estimation at the first iteration. The system throughput is gradually optimized and converged by iteration according to the adaptive estimation. After convergence, the system throughput is improved up to approximately 40% compared to the conventional CSMA/CA when I_{init} is 100. Faster convergence of the length of the Post-IFS, P_n (x), is achieved by setting a larger I_{init} value according to the results shown in Fig. 3.25. However in Fig. 3.24, a smaller I_{init} value can obtain better system throughput. The reason for this is explained as follows. Step-size α (x) is compulsorily and gradually decreased according to Eq. (3.9). Therefore, forced convergence is achieved. Moreover, a larger I_{init} value changes the estimated length of the Post-IFS, P_n, dynamically. This dynamic change in P_n provokes a faster forced convergence of P_n. On the other hand, a smaller I_{init} value changes P_n finely and this enables the adaptive estimation to provoke a slower forced convergence of P_n. As a result, the speed of convergence and degree of accuracy for the search for the optimal value has a trade-off relationship similar to that in the steepest decent scheme.

Therefore, it is clarified that the proposed scheme with the adaptive estimation improves the system performance without knowing the information regarding each STA.

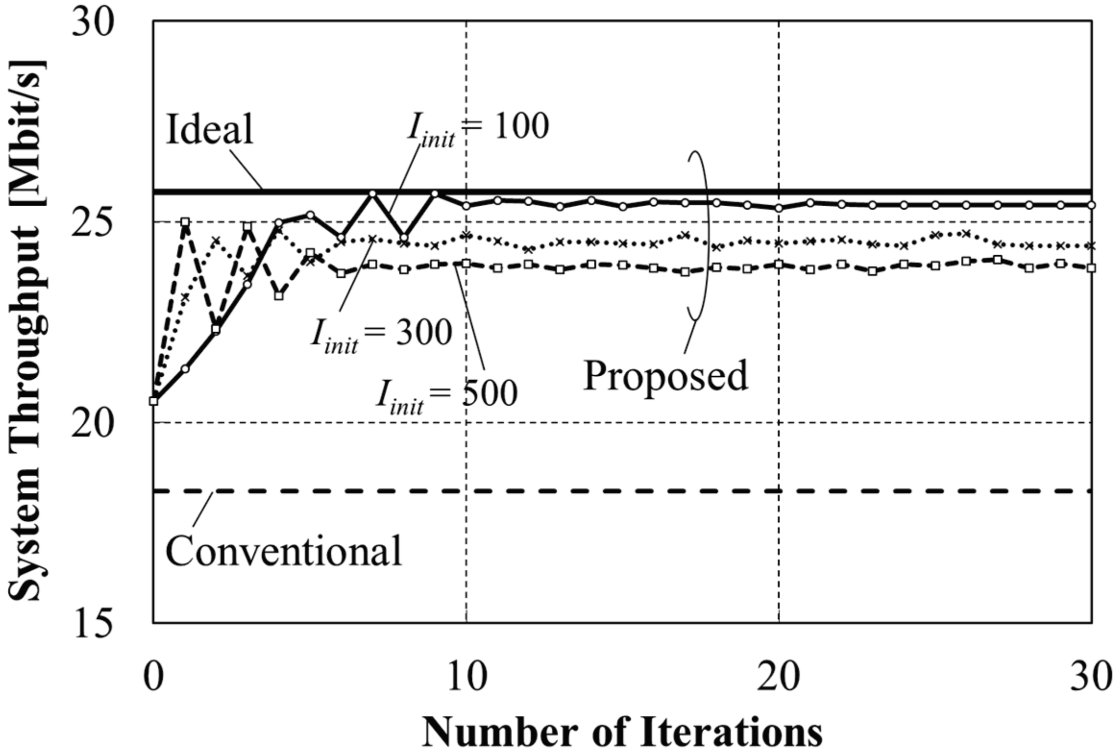

Fig. 3.24 Progress in system throughput optimization.

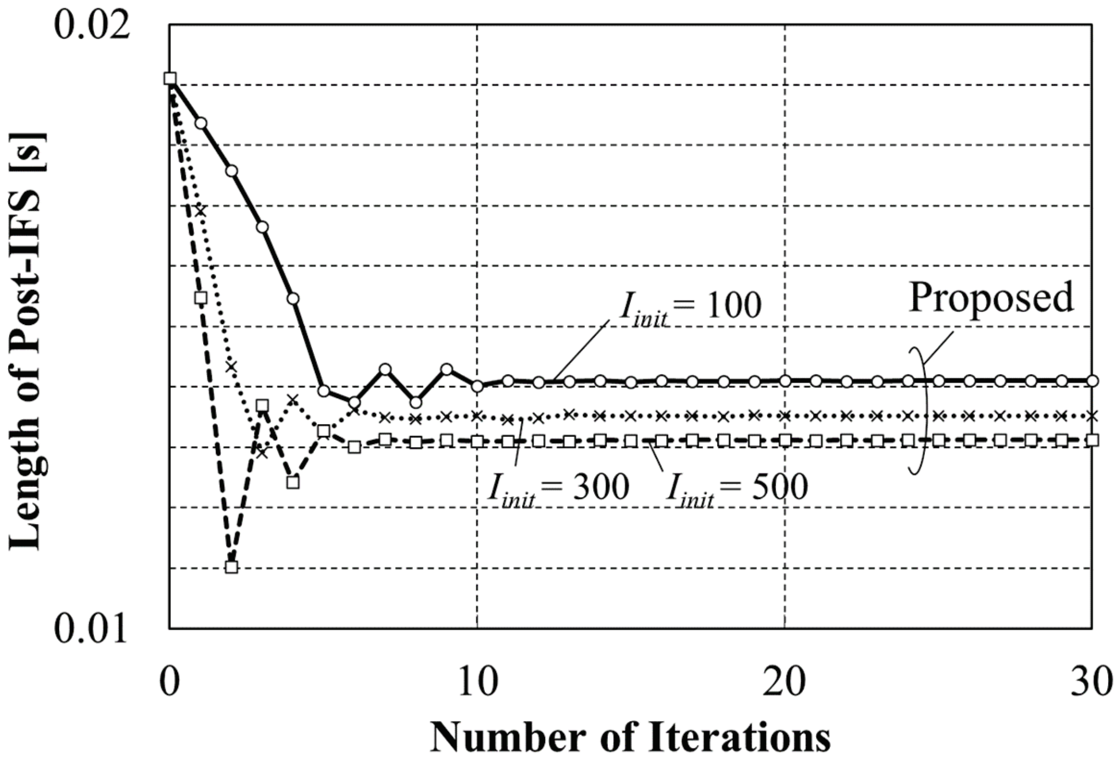

Fig. 3.25 Progress in length of Post-IFS optimization.

3.4.4. Experiment 1: Effect of Post-IFS

In this subsection, the effect of the length of the Post-IFS is evaluated. In this experiment, all STAs associates one AP and each STA sends User Datagram Protocol (UDP) traffic to the AP under saturated conditions. Moreover, Auto Rate Fallback (ARF) that gradually reduces the transmission rate when the transmission fails is not applied and the transmission rate of each STA is constant. Under this condition, the system throughput characteristics to the length of the Post-IFS are evaluated for both the proposed scheme and the conventional CSMA/CA. The results are shown in Fig. 3.26. In Fig. 3.26, the conventional CSMA/CA has a constant value to any value of Post-IFS because the conventional CSMA/CA does not set any Post-IFS after the transmission regardless of its setting of the Post-IFS value. On the other hand, the more the length of the Post-IFS gets large value, the more the system throughput improves in the proposed scheme till it reaches the peak value. After the peak, the system throughput degrades according to the length of the Post-IFS. This is because the frame collision probability decreases due to reduction of the number of competing STA according to the length of the Post-IFS as described in Subsection 3.3.3. However, after the peak value, the period in which no STA can perform transmission is generated due to the extra duration of the Post-IFS. This degrades the system throughput and its drawback overwhelms the effect of collision reduction in this area. Therefore it is verified according to the result that the degree of improvement in the system throughput depends on the trade-off between the reduction in the collision probability and the length of extra overhead.

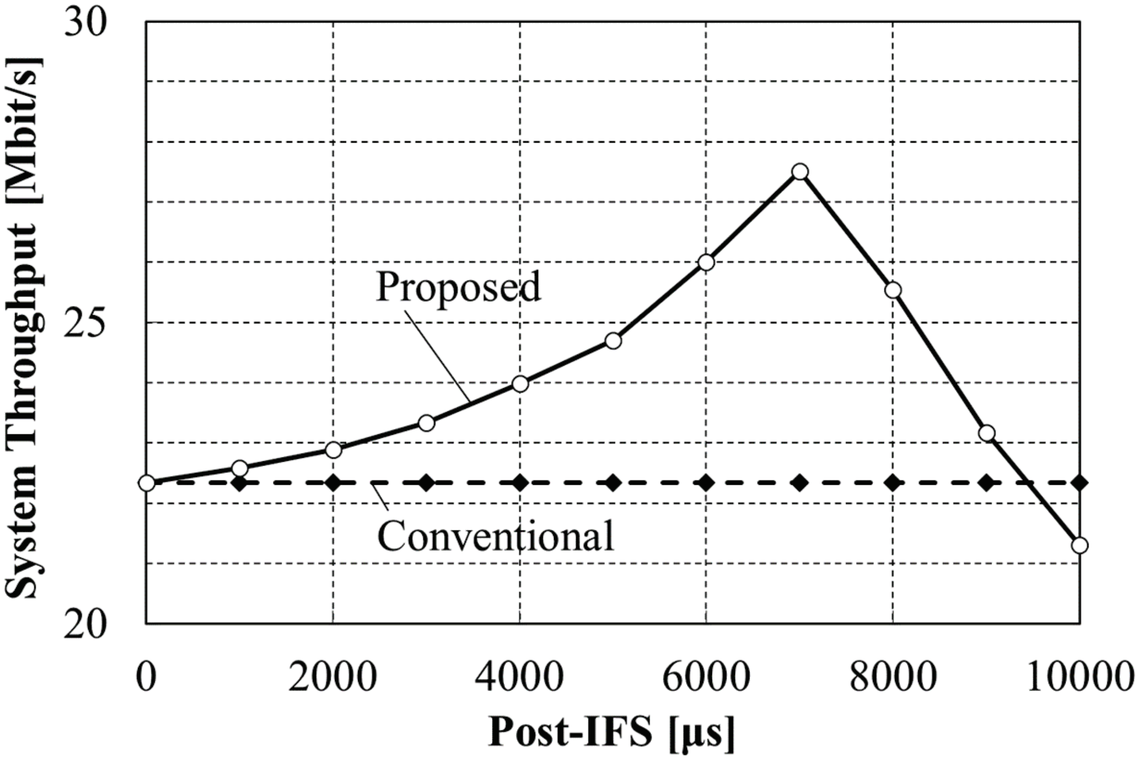

Fig. 3.26 System throughput vs. length of Post-IFS (experiment).

3.4.5. Experiment 2: Maximum Performance

The system throughput versus the number of STAs is evaluated in this subsection. In this experiment, it is assumed that the payload size of data frames S_i is constant and the size is 1470 bytes based on the maximum size of an UDP socket. The transmission rate R_i is also constant and the ARF is not applied as well as Experiment 1. Moreover, it is assumed that the estimation of S_i and R_i are perfect at each STA. Therefore the length of the Post-IFS for each STA is determined according to Eq. (3.5) in advance.

The experimental result under saturated conditions is shown in Fig. 3.27. Unlike the results from Subsection 3.4.1, the system throughput of the proposed scheme decreases in proportion to the number of STAs. The reason of this phenomenon is considered as follows. The hardware device has a margin of error with an uncertainty of 100 μs and this disturbs the accurate setting of the length of the Post-IFS. Furthermore, there are Beacon frames that are broadcasted by the AP and the duration of the Beacon frame is not considered in Eq. (3.5). Therefore, it leads to have a few collisions and the tendency for the system throughput is similar to that for the conventional CSMA/CA in the proposed scheme. This is the difference between simulation evaluations and experimental evaluations. However, even allowing for the difference, the proposed scheme outperform the conventional CSMA/CA in the system throughput. According to Fig. 3.27, the proposed scheme achieves 23% higher throughput than that for the conventional CSMA/CA when N is 19. This amount of the improvement is nearly the same as that of the simulation evaluation.

Next, these characteristic under non-saturation conditions is evaluated. In this evaluation, frames to send are generated periodically according to setting of UDP bandwidth and the number of STAs is set to 19. The system throughput versus the offered traffic load is evaluated. The result of the experiment is shown in Fig. 3.28. According to the result shown in Fig. 3.28, the proposed scheme and the conventional CSMA/CA achieve the same throughput when the offered traffic load is less than 20. When the offered traffic load exceeds 25, the traffic flow becomes saturated in the conventional CSMA/CA and the proposed scheme achieves higher throughput. The traffic flow of the proposed scheme becomes saturated when the offered traffic load exceeds 30. Despite the existence of the Post-IFS, the reasons why the proposed scheme can obtain throughput equal to the conventional CSMA/CA under non-saturated conditions are the same as mentioned in Subsection 3.4.1. Moreover, the tendency of the system throughput characteristics are almost same between the simulation evaluations and the experimental evaluations. As the overhead time derived from Beacon frames is not considered as well in the simulation evaluations, the slight difference between those two evaluations is generated.

Therefore, it is verified that the proposed scheme improves the system performance under actual environment compared to the conventional CSMA/CA by reducing the number of collisions.

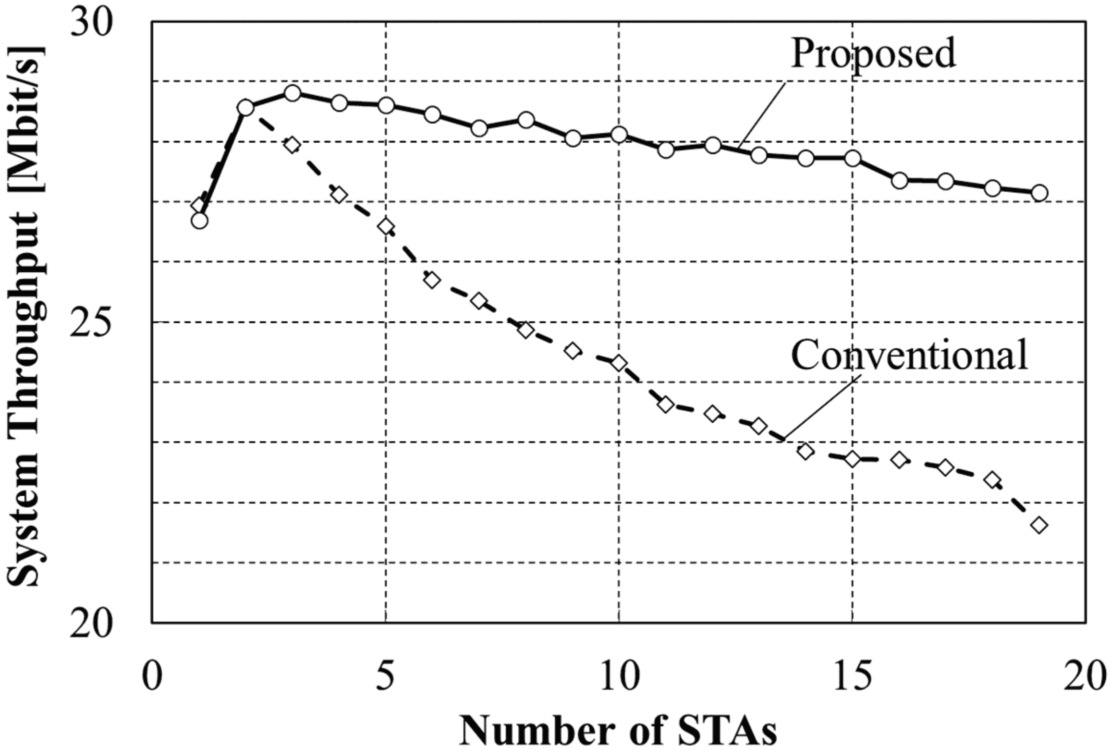

Fig. 3.27 System throughput vs. number of STAs (experiment).

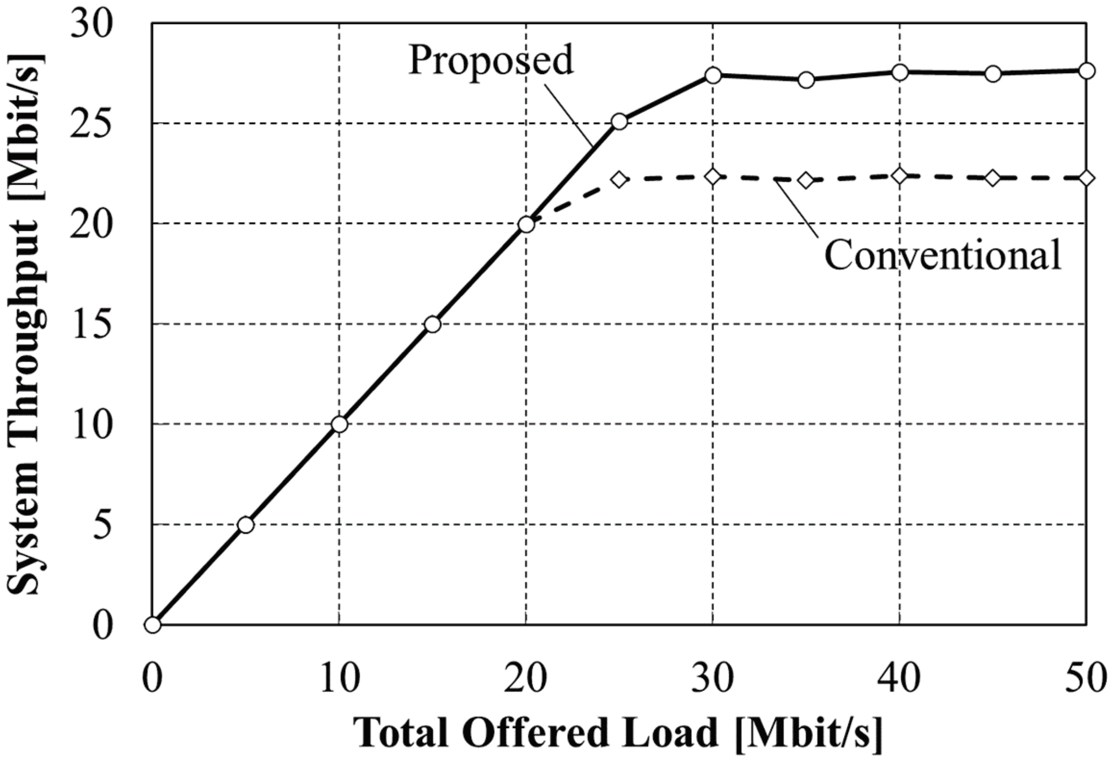

Fig. 3.28 System throughput vs. offered traffic load (experiment).

3.5. Summary

In this chapter, a simple scheme that decreases the number of frame collisions by refraining from transmission during the Post-IFS after a successful transmission was proposed. The proposed scheme is easy to implement into existing WLAN devices because no original frames need to be defined and it has only a slight impact on the existing CSMA/CA protocol. The proposed scheme improves the system performance including the throughput characteristics, access delay and the number of retransmissions by reducing the number of collisions. The length of the Post-IFS is a key factor in improving the system performance for the proposed scheme. If the AP can estimate the optimal value of the Post-IFS, collision-free operation similar to that in non-contention based protocol is performed. Even if the optimal Post-IFS is not estimated, the number of competing STAs and the collision probability are decreased. Two estimation methods are also introduced: one is fixed estimation that specifies the value of the Post-IFS using the distribution of observed frames, and the other is adaptive estimation that is based on the fixed estimation and utilizes the idea of the steepest descent method to explore the optimal value for the Post-IFS.

The effects of the proposed scheme were verified based on computer simulations and experiments. The proposed scheme is effective in particular in a wireless dense environment under both saturated and non-saturated conditions. The results of the computer simulations showed that the proposed scheme achieves up to 40% higher system throughput compared to the case in which the proposed scheme is not introduced.

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Chapter 4

User-Oriented QoS Control Scheme based on CSMA / CA

4. User-Oriented QoS Control Scheme based on CSMA / CA

4.1. Introduction

As described in Chapter 2, the CSMA/CA is designed in such a way that the priority for transmission from all STAs is impartial. However, to improve the user experience, there are many cases where certain STAs should be given priority. This priority structure is defined as a user-oriented QoS. In the following cases, protecting user-oriented QoS becomes important: the case where all STAs or APs are controlled by site owners or residents, or the case where priorities for certain STAs are obvious according to the STA service policy or regulations. The use of WLANs in offices or homes, the use for presentations at an exhibition, the use of fee-based Wi-Fi hotspots are examples of these cases. On the other hand, the IEEE 802.11e EDCA [4.1] provides a QoS mechanism for the DCF as described in Chapter 2. However, the EDCA prioritizes each traffic flow based on categorized applications and not based on specific STAs. In other words, the EDCA does not protect user-oriented QoS aimed at specified STAs. The priority structure protected by the EDCA is defined as application-oriented QoS.

On the other hand, the IEEE 802.11 defines non-contention based centralized control schemes: the PCF and the HCCA as mentioned in Chapter 2. The system throughput characteristics of these centralized control schemes are superior to those for the DCF. Moreover, these centralized operations are able to control QoS using arbitrary criteria that specify the timing of transmission. Ref. [4.2] utilizes the existing framework of the PCF and increases the flexibility of QoS by using an IEEE 802.11e-type scheduler. Ref. [4.3] proposes an aging priority scheduling algorithm and a dynamic adaptation algorithm to vary the PCF interval based on the traffic and to reduce the overhead. Ref. [4.4] introduces an enhanced polling scheme that manages queue control.

Although these polling-based control schemes achieve good performance and QoS control, I focus on contention based schemes such as the DCF because of the inherent problem with complete polling mechanisms described in Chapter 2. This is because if there are many DCF STAs, these polling-based control schemes have difficulty with flexible operation when trying to coexist with the DCF STAs because those polling schemes utilize the Network Allocation Vector (NAV) and the NAV prohibits any transmission of the DCF STAs. In the PCF, the DCF STAs cannot transmit any data frame unless this NAV period ends. This mechanism causes degradation in the throughput and delay characteristics for the DCF STAs. Moreover, in the HCCA, the AP is required to schedule the timing and estimate the duration of transmission for each STA using procedures such as TSPEC negotiation defined in the IEEE 802.11e. This *a priori* procedure degrades the throughput and delay characteristics as well. In addition, most well-known WLAN STAs adopt the DCF and it is easy to implement contention based control especially in a wireless dense environment.

Therefore, this chapter proposes an effective MAC protocol based on the CSMA/CA that protects user-oriented QoS for each STA. More specifically, the proposed scheme protects user-oriented QoS by operating the CSMA/CA as a pseudo-centralized control that utilizes two kinds of fixed back-off as substitutes for random back-off. The proposed scheme coexists with the conventional DCF and is able to prioritize specified STAs. Thus, the proposed scheme is highly effective in the cases described above, and can coexist with other WLAN systems by controlling the priority between the proposed STAs and other conventional DCF STAs. Moreover, the proposed scheme is effective under saturation conditions, which means that STAs always have data to send. It is considered that these saturation conditions are generated frequently in a wireless dense environment.

In the proposed scheme that will be explained hereafter, although the concept of its operation is based on centralized control, the actualization procedure is based on the DCF. Therefore, the proposed scheme avoids the problems facing the complete polling-based schemes described above. It aims to achieve coexistence with the DCF STAs and enhance the communication quality without using the complete polling mechanisms.

4.2. QoS Control for WLAN

As described in Subsection 2.3.2, there are many notable studies that combat the problem concerning QoS control for WLAN systems. In Ref. [4.5], a user-oriented QoS protection method using the EDCA is proposed. The method converts each AC corresponding to a single application into an AC corresponding to a single specified STA. This method utilizes the existing EDCA framework; however, the resulting plethora of queues for the number of STAs significantly increases the implementation costs. Moreover, the method cannot prevent collisions generated between prioritized STAs because of the CSMA/CA operation. Therefore, the method does not prevent throughput degradation, especially in a wireless dense environment.

To prevent throughput degradation, other studies focus on improving the CSMA/CA [4.6]-[4.12]. The main approach employed in these studies is adaptive optimization of the CSMA/CA parameters such as the CW or IFS. The number of STAs (Ref. [4.6] and Ref. [4.7]), transmission rate (Ref. [4.8] and [4.9]), and frame size (Ref. [4.10] and [4.12]) are utilized to appraise metrics. The transmission history and ARF are criteria used to adjust the optimal parameters in Ref. [4.10]-[4.12]. Most of these methods dynamically change the CW to decrease the possibility of collision. Subsequently, the CW is gradually adjusted to an appropriate value as determined by the criterion of each method. These methods can improve the system throughput without drastically changing the existing CSMA/CA. However in these methods, protection of the user-oriented QoS is difficult with coexisting the conventional DCF STAs. This is because the DCF STAs deprive other STAs of priority by resetting their CW to the head start value (CW_{min}) after each successful transmission. Therefore, protection of user-oriented QoS is difficult with coexisting conventional DCF STAs.

Then again, Ref. [4.13]-[4.19] propose other remarkable approaches that utilize both polling based and contention based control. Ref. [4.13] proposes a polling ACK mechanism to permit the designated STA to transmit without performing any contention process in the DCF. Ref. [4.14] proposes a QoS control method by a priority-based back-off scheme to provide application-oriented QoS. Moreover, the methods in Ref. [4.15] and Ref. [4.16] utilize both fixed back-off and random back-off by sending the back-off timer information together with the data or control frames destined to each given STA.

The work herein is most relevant to the work done in Ref. [4.17]-[4.19]. In Ref. [4.17], a method referred to as the CSMA/Enhanced Collision Avoidance (ECA) operates with pseudo-centralized control by using a fixed back-off. The CSMA/ECA assigns its back-off value randomly with its first transmission as well as that for the CSMA/CA. A fixed back-off value is assigned for successive transmissions. If there is no collision for the first transmission, all STAs can avoid collision on consecutive transmissions. On the other hand, if the transmission fails owing to a collision between a fixed back-off transmission and a random back-off transmission (for example, a transmission from a DCF STA), a random back-off value is assigned again for the CSMA/ECA STA. This operation further facilitates coexistence with the DCF STAs.

However, it is difficult to maintain pseudo-centralized control using a fixed back-off when random back-off transmissions exist because if the previous transmission fails due to a collision, a random back-off value is assigned instead of a fixed back-off value for the CSMA/ECA STA. Thus, the number of STAs using a random back-off increases and this increases the possibility of collision. Even if there are no DCF STAs, collisions between the CSMA/ECA STAs cannot be eliminated because of the initial random back-off.

4.3. Proposed Scheme

In this section, a flexible pseudo-centralized control scheme is proposed. The proposed scheme uses two kinds of fixed back-off to protect user-oriented QoS in an environment with coexisting DCF STAs and improves the throughput characteristics. The basic idea is described in Subsection 4.3.1. The detail of the two kinds of fixed back-off is explained in Subsection 4.3.2. The effect of control of user-oriented QoS is discussed in Subsection 4.3.3.

4.3.1. Basic Operation

The basic access mechanism and the flowchart for the proposed scheme are illustrated in Fig. 4.1 and Fig. 4.2. The proposed scheme is based on the CSMA/CA and the functions of the proposed scheme for CS, decreasing the back-off, and IFS parameters are the same as those for the CSMA/CA. The significant difference from the CSMA/CA is how the back-off value is determined. Although the CSMA/CA decides the back-off value randomly within the CW range, the proposed scheme defines and adopts two kinds of fixed back-off values, namely, the Initial Back-off Value (IBV) and the Cyclic Back-off Value (CBV). The AP specifies the IBV and assigns it as the back-off value when the first transmission of each STA occurs. The IBV is a unique and non-zero value that is different for each STA. During the first transmission occurs, there is no collision between the STAs using the proposed scheme (hereafter proposed STAs) due to the different back-off values decided by the IBV. Afterwards, the CBV is assigned as the back-off value for each successive transmission unless a collision occurs. The CBV is also a fixed value and is specified by the AP. However, the value is common to all proposed STAs. The effect of the two kinds of fixed back-off values can be summed up as follows. The IBV establishes different offset times for each STA, while the CBV sustains the relation of the offset in a cyclic manner. This operation avoids collisions between the proposed STAs and improves the system throughput.

During the pseudo-centralized control of the proposed scheme, DCF STAs can execute their transmissions as usual, unlike existing centralized control schemes, as illustrated in Fig. 4.3. This is because the proposed STAs are different from the DCF STAs only in the way they determine back-off values, while they refrain from transmissions during “busy” state according to the CSMA/CA manner. As a result, the periodicity of the back-off value for the proposed STAs is maintained as long as the DCF STAs assign back-off values that are different than those for the proposed STAs.

Although collision between proposed STAs can be avoided, there is a possibility that they will collide with DCF STAs. Fig. 4.4 illustrates the operation of the proposed scheme when the transmission of a proposed STA collides with that of a DCF STA. In this case, all the proposed STAs reset their back-off values to each specified IBV using the “Initial Back-off Reset Frame” (IBRF). While the DCF STA expands its CW to reduce the collision probability based on the BEB, the proposed STAs resume pseudo-centralized control of the initial stage. Since the back-off values of the proposed STAs are reset to their IBV each time a collision occurs, assignment of the IBV is the key factor in deciding the user-oriented QoS level. In other words, if a low number is assigned to the IBV, the priority of proposed STA increases and vice versa. The effect of IBV and CBV is explained in Subsection 4.3.3.

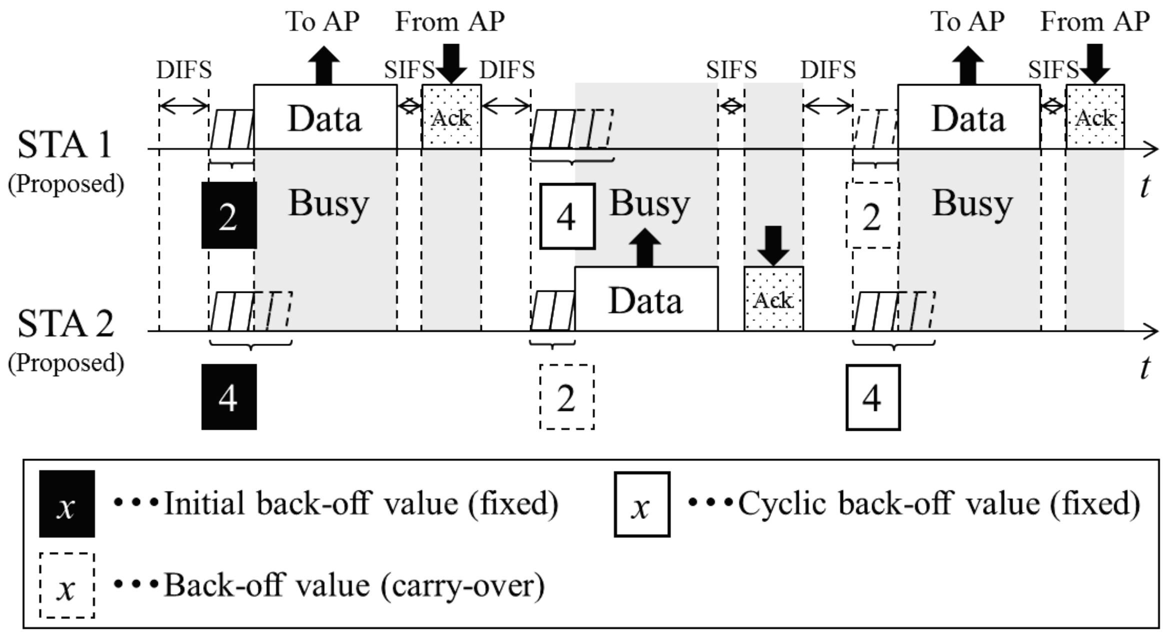

Fig. 4.1 Basic operation of proposed scheme.

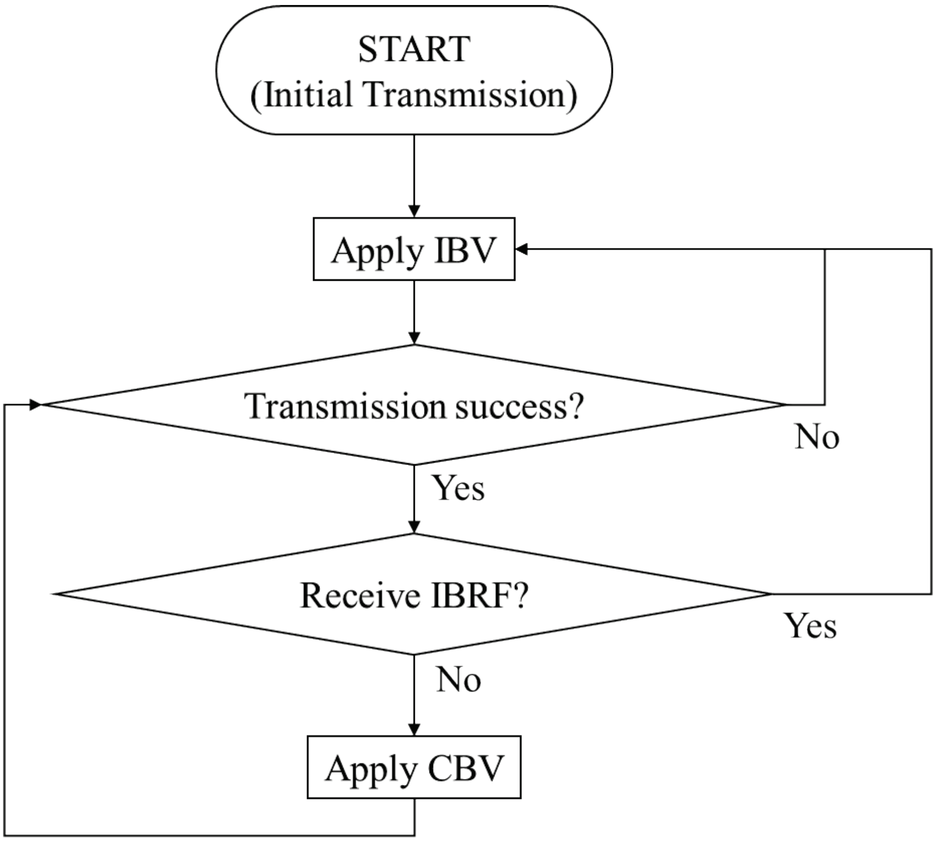

Fig. 4.2 Flowchart of the proposed scheme.

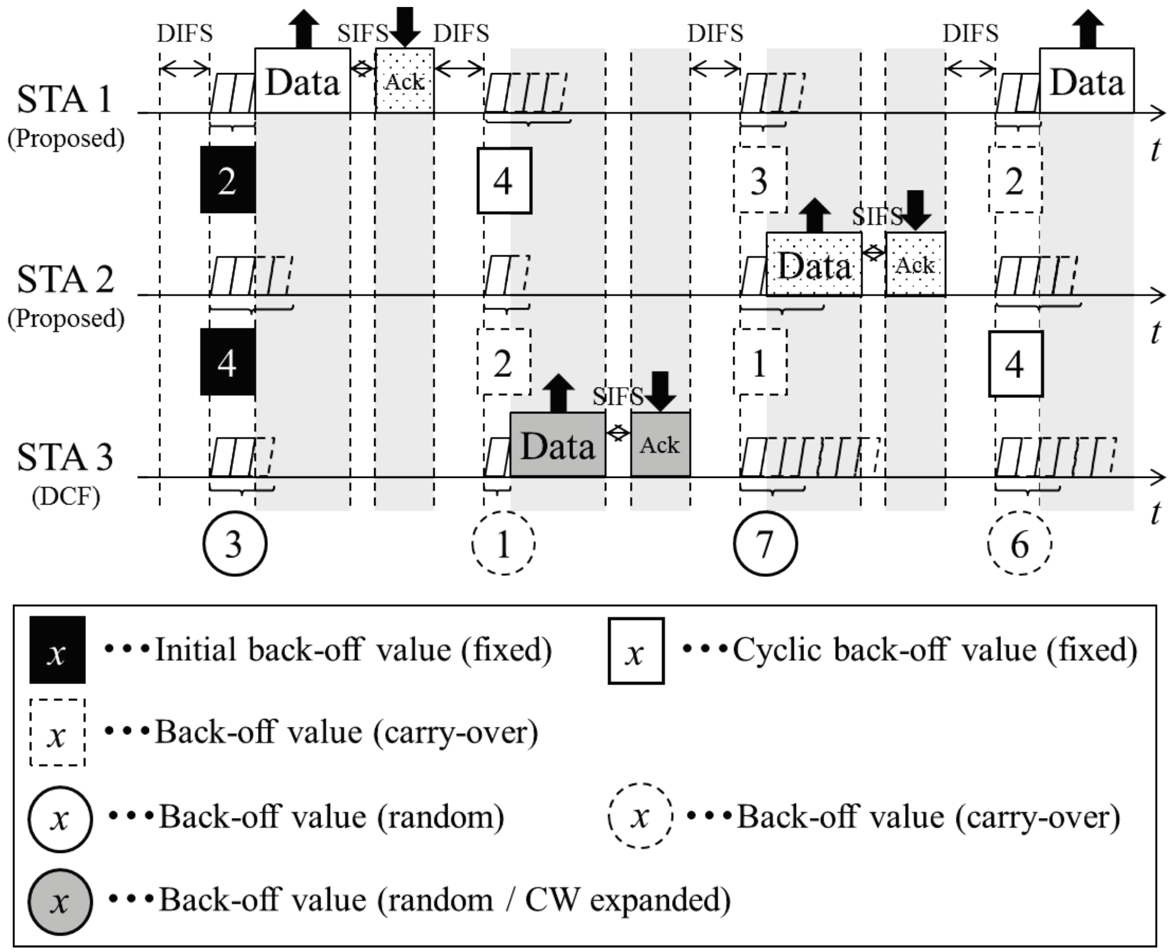

Fig. 4.3 Operation of proposed scheme with DCF STA.

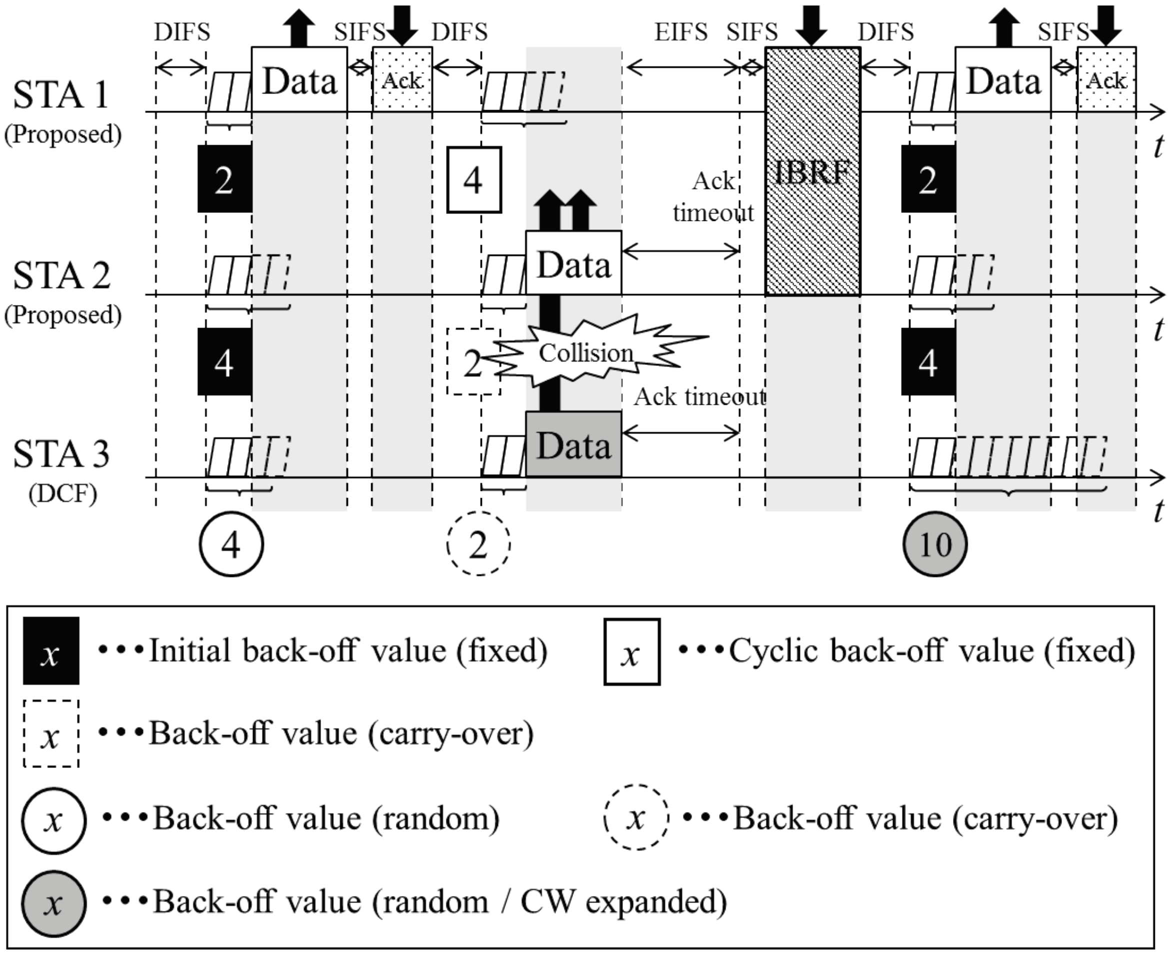

Fig. 4.4 Operation of proposed scheme with DCF STA (Collision).

4.3.2. Fixed Back-off Values

If only proposed STAs are connected to an AP, i.e., there are no DCF STAs, there is no prioritization among the STAs because the proposed scheme implements complete centralized operation without any collision and the chances for transmission are given in a cyclic manner. However, in a situation where a collision occurs due to DCF STAs, the back-off values for each proposed STA are reset to each specified IBV upon a collision. This behavior can be leveraged to control the user-oriented QoS. The degree of the QoS depends on the settings for the CBV and IBV described as follows.

1) **Cyclic Back-off Value (CBV)**

   The CBV is a shared value among all proposed STAs and is assigned to consecutive transmissions as long as the previous transmission is successful. The number of CBV values should be equal to or greater than the total number of all STAs including DCF STAs. A larger CBV can better decrease the possibility of collisions between proposed STAs and DCF STAs. Conversely, if the number of CBV values is less than the total number of all STAs, a collision is inevitable due to lack of selectable back-off values. This CBV is broadcasted via a beacon frame or an IBRF.

2) **Initial Back-off Value (IBV)**

   The IBV is a unique value assigned to each proposed STA and is applied when STAs receive an IBRF from an AP. The AP informs each STA of the specified IBV using a probe response frame or data frame. At this point, the same IBV should not be assigned to different STAs. Moreover, the value of each IBV should not exceed the CBV; in other words, any IBV should be within the cycle length of the CBV. Each proposed STA that receives the IBRF immediately resets its back-off value to its assigned IBV. Therefore, STAs that have a lower IBV can obtain more chances for transmission. As a result, priority control for each proposed STA is enabled by adjusting the IBV appropriately. In addition, the IBRF is broadcasted when the initialization of pseudo-centralized control is desired; that is, when a new STA connects to the AP or a collision occurs. Although it is possible for proposed STAs to maintain pseudo-centralized control without any IBRF if all the proposed STAs can detect collisions and autonomously reset their back-off values to their respective IBVs, this situation may cause unconformity in the back-off resulting from the hidden terminal problem. Therefore, it is preferable to broadcast an explicit IBRF to all the proposed STAs to eliminate this problem. Furthermore, although the proposed scheme is aimed at use in a wireless dense environment, it can be utilized in a non-wireless dense environment. In order to maintain the basic operation of the proposed scheme, a CBV is assigned without transmitting any data frame if there are no data to send in the queue of the proposed STA when the proposed STA obtains a chance for transmission. However, the overhead time due to unnecessary back-off degrade the throughput and delay characteristics. Therefore, if data transmissions occur sporadically, the proposed scheme can quit the pseudo-centralized operation and change to the CSMA/CA. This hybrid operation can cope with the case where only a specific STA has much data to send as well.

4.3.3. Control of User-Oriented QoS

Hereafter, the priority structure between the proposed scheme and the conventional DCF is defined as the system level user-oriented QoS (S-QoS). The priority structure of each proposed STA is defined as the user level user-oriented QoS (U-QoS) as well.

There are two methods to control the S-QoS. One is to expand the range of the CBV and the other is to adjust the IBV. First, some variables to express the effects of these two fixed back-off values are defined. It is assumed that N STAs are connected to the AP and these STAs comprise both proposed and DCF STAs. In addition, the total number of the proposed STAs is assumed to be N_p and the total number of the DCF STAs is N_c. An individual STA number, n (n = 1, 2 … N) is given to each STA. Therefore, the AP decides the IBVs and CBV for the proposed STAs in the range of the following formulas.

$$B_c \geq N \, , \tag{4.1}$$

and

$$B_c \geq B_I(n) . \tag{4.2}$$

In Eqs. (4.1) and (4.2), B_c represents the shared CBV of all the proposed STAs and B_I (n) denotes the IBV of STA n.

The effect of expanding the range of CBV is described below. The total number of candidates for the back-off value of DCF STAs that avoid collisions is B_r and is calculated as follows,

$$B_r = B_c - N_P \tag{4.3}$$

According to Eq. (4.4), a larger B_c can increase B_r further. This means that the possibility of collision between the proposed STAs and DCF STAs is decreased and the DCF STAs obtain more chances for transmission in exchange for a reduction in the number of chances for transmission for the proposed STAs in proportion to B_c. Fig. 4.5 shows the flowchart for the setting of CBV to control the S-QoS, and Fig. 4.6 shows an example of the effect of expanding CBV respectively. There are four proposed STAs (N_p = 4), one DCF STA (N_c = 1), and the total number of STAs is five (N = 5). If B_c is set to five (which, in this case, equals N), the proposed STAs receive a chance of transmission every five back-off slots if no collision occurs. This enables high-speed transmission for the proposed STAs. However, the transmission of the

DCF STA collides with the transmission of the proposed STA with a probability of 4/5. If B_c is set to ten (which equals $N \times 2$), the collision probability of the DCF STA drops to 2/5 by means of degrading the efficiency and priority of the proposed STAs. In this case, the efficiency and priority of the DCF STAs are improved at the expense of the proposed STAs.

Next, the method of controlling the S-QoS by adjusting IBV is explained. Fig. 4.7 shows the flowchart for the setting of IBV to control the S-QoS. In addition, Fig. 4.8 illustrates the relationship between IBV and S-QoS. As described in Subsection 4.3.2, a proposed STA with a lower IBV has a higher priority level. Thus, the method to assign the higher priority to the proposed STAs is to set each IBV in ascending order. Namely, each $B_I(n)$ is assigned as follows,

$$B_I = \{B_I(n) \mid B_I(n) = 1, 2, \cdots, N_p\}. \tag{4.4}$$

In contrast, the method to prioritize DCF STAs is to set each IBV in descending order as expressed below,

$$B_I = \{B_I(n) \mid B_I(n) = B_c, B_c - 1, \cdots, B_c - N_p + 1\}. \tag{4.5}$$

Therefore, control of the S-QoS is achieved through these two methods.

The grade of the U-QoS depends on each IBV assigned to each proposed STA. For example, the allocation method in Eq. (4.4) divides the U-QoS into N_p classes (the same as the number of proposed STAs). Moreover, the proposed scheme classifies the U-QoS by arbitrary granularity. This is achieved by changing the IBV adaptively upon a collision. It is assumed that n_p is the individual STA number for the proposed STA and c is the number of collisions. Moreover, x_q represents the granularity of the U-QoS class. Then n_p is set as shown in Eq. (4.6) as an example,

$$n_p = 1, 2, \cdots, N_p. \tag{4.6}$$

Therefore, the allocation method of the IBV that controls the U-QoS class between the proposed STAs is expressed as follows,

$$B_I(n_p)[c+1] = \begin{cases} B_I(n_p + x_q)[c] & (n_p + x_q \leq N_p) \\ B_I(n_p + x_q - N_p)[c] & (n_p + x_q > N_p) \end{cases}. \tag{4.7}$$

In Eq. (4.7), where B_I (n_p) [c] is the IBV of the proposed STA whose number is n_p after c collisions. The IBV is assigned in turn among the proposed STAs. If x_q = 1, the priority of each proposed STA is removed. Fig. 4.9 depicts an example of this operation and Fig. 4.10 shows the flowchart for the setting of the IBV to control U-QoS respectively.

In addition, individual U-QoS control for each STA is achieved by manually classifying groups of STAs for IBV rotation. It is assumed that g is the arbitrarily group number and it equals the priority rank. Each group g contains any number of STAs that is arbitrarily classified by the controller of the AP. The assignment of each IBV and its rotation rule are expressed below.

$$B_I(n_p)[c+1] = \begin{cases} B_I(n_p+1)[c] & \left(n_p + 1 \leq n_{p(g,\max)}\right) \\ B_I(n_{p(g,\min)})[c] & \left(n_p + 1 > N_{p(g,\max)}\right) \end{cases}, \tag{4.8}$$

where $n_{p(g,\max)}$ and $n_{p(g,\min)}$ are the maximum STA number and the minimum STA number that belong to group g, respectively. Therefore, the granularity of the U-QoS class is decided arbitrarily according to the classification number. Moreover, the priority levels of the proposed STAs that belong to the same group become the same although the difference in the priority level between each group remains. Thus, the priority level between proposed STAs (U-QoS) can be controlled by setting an appropriate IBV.

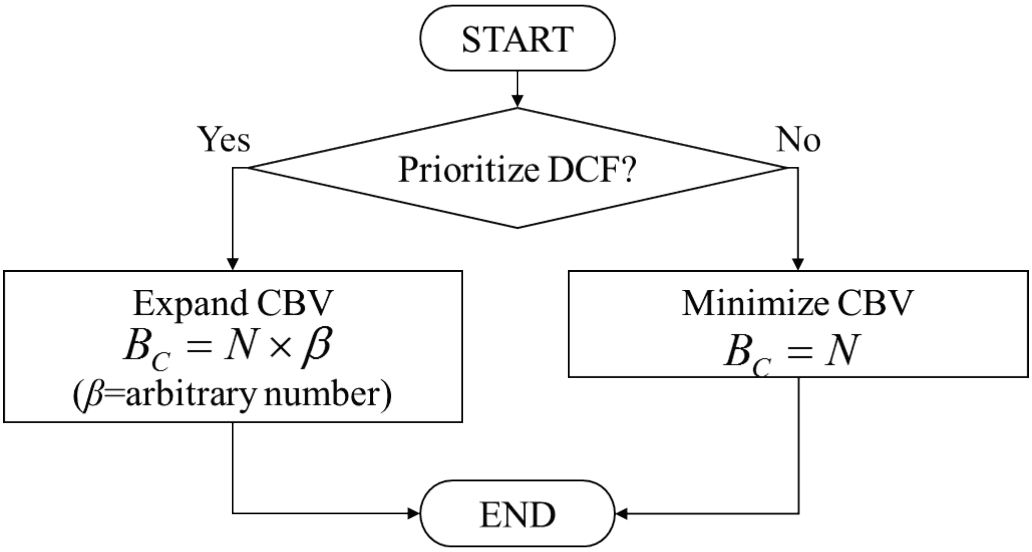

Fig. 4.5　Flowchart of S-QoS control (by CBV).

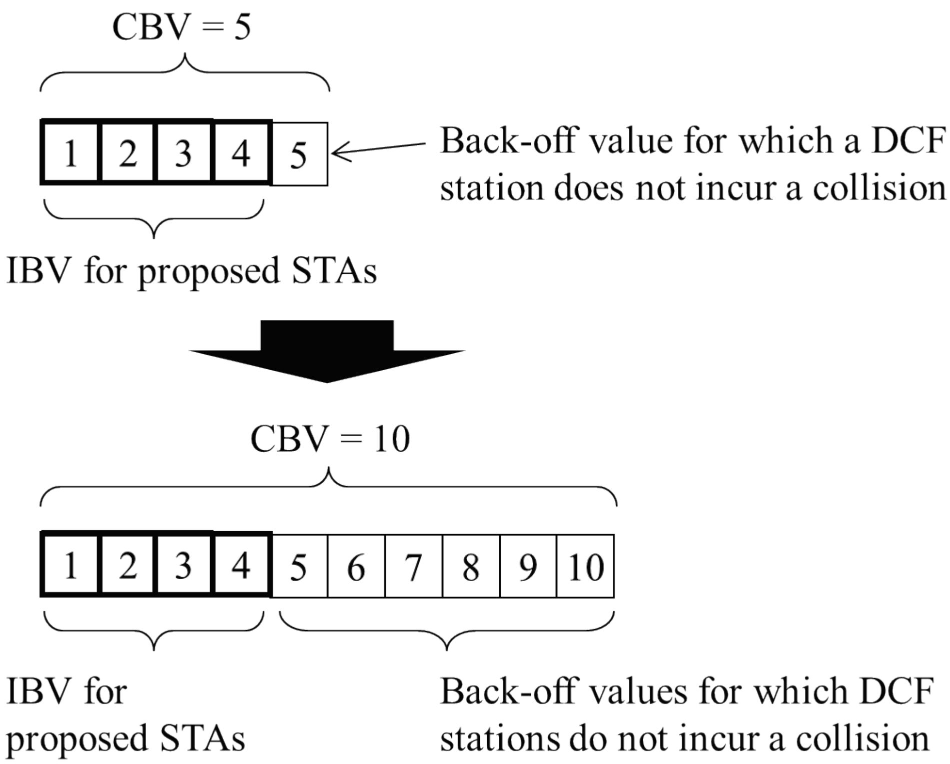

Fig. 4.6　Effect of expanding CBV.

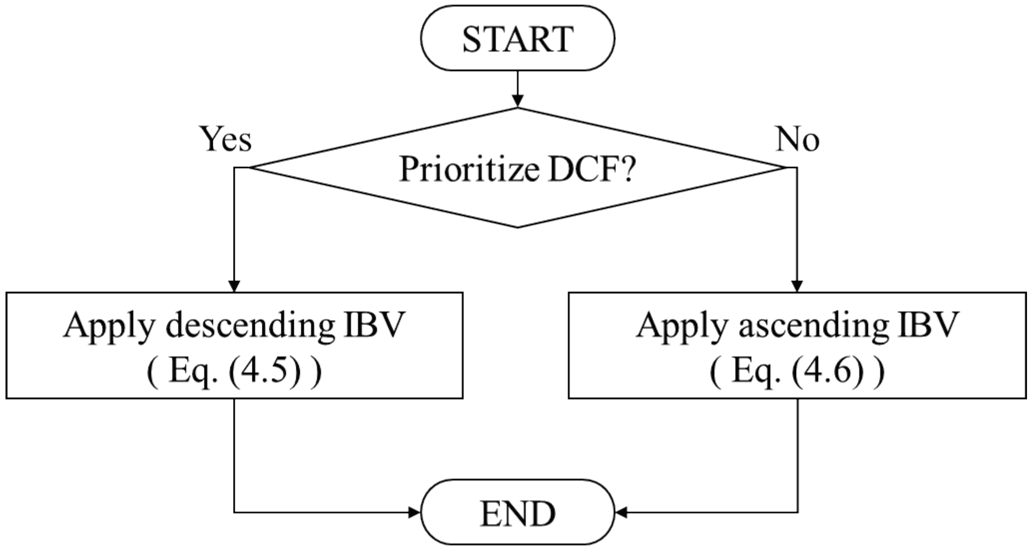

Fig. 4.7 Flowchart of S-QoS control (by IBV).

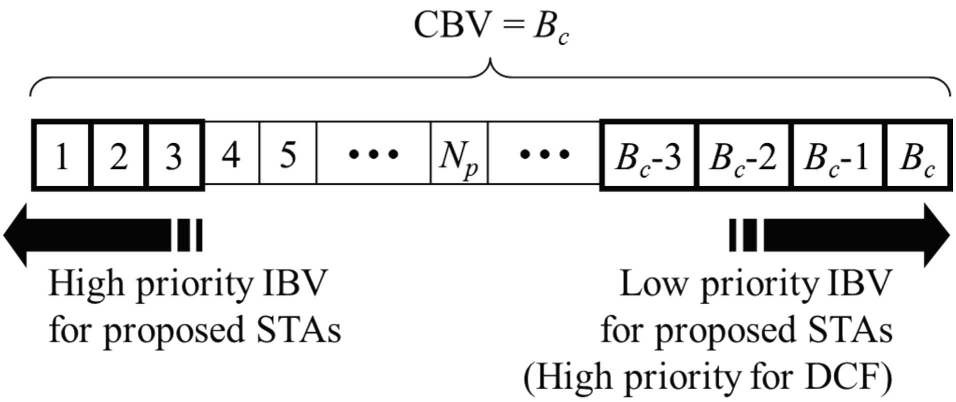

Fig. 4.8 Priority control by adjusting IBV.

STA Number. n		1	2	3	…	n_p	…	N_p-1	N_p
B_I	$[c\text{-}1]$	1	2	3	…	n_p	…	N_p-1	N_p
	$[c]$	2	3	4	…	n_p+1	…	N_p	1
	$[c+1]$	3	4	5	…	n_p+2	…	1	2
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

From 1

Fig. 4.9 Assignment of IBV for user-oriented QoS (x_q = 1).

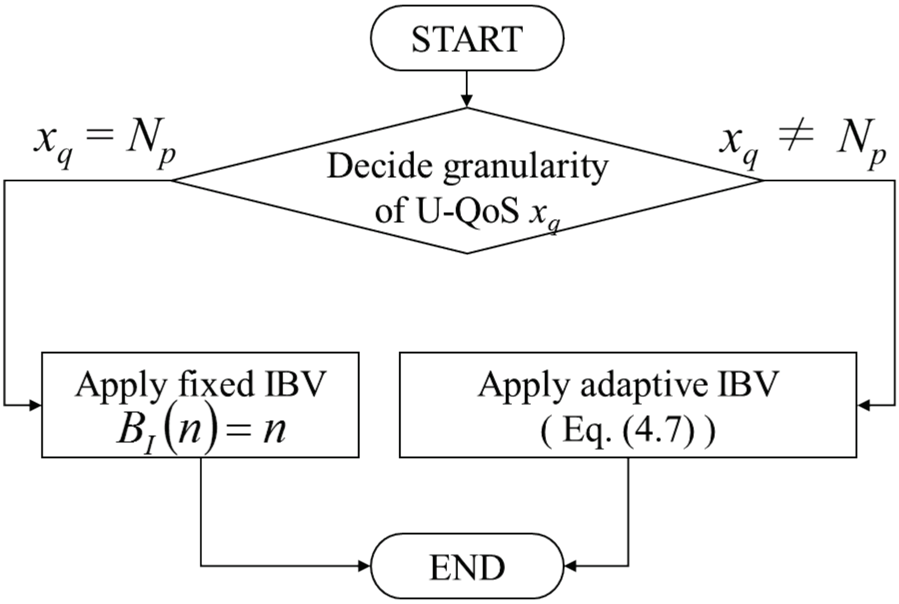

Fig. 4.10 Flowchart of U-QoS control (by IBV).

4.4. Performance Evaluation

To clarify the performance of the proposed scheme, computer simulations are conducted. Firstly, the maximum performance of the proposed scheme, the DCF, and the CSMA/ECA as introduced in Ref. [4.17] are evaluated. Secondly, the impact of controlling the S-QoS is evaluated in an environment where the proposed and DCF STAs coexist. Finally, it is verified that whether or not the U-QoS can be protected in an environment where the proposed and DCF STAs coexist. The simulation parameters are listed in Table 4.1. Parameters such as the IFS and slot time comply with the IEEE 802.11g. Moreover, these simulations are operated under saturation conditions, which mean that STAs always had data to send. Besides, these simulations are conducted with the simulation time of 20 s, and the results of these simulations are derived from the mean value of that period.

Table 4.1 Simulation parameters.

Parameter	Evaluation 1	Evaluation 2		Evaluation 3
		(i)IBV	(ii)CBV	
Number of STAs N	1-50	50		
Proportion of Proposed STAs α_q	0 and 1	0 to 1	0.5	0.3
Transmission Rate [Mbit/s]	54			
Data Payload [byte]	1500			
Maximum Retry	6			
SIFS [μs]	16			
DIFS [μs]	34			
SlotTime [μs]	9			
Initial Backoff Value $B_I(n)$ (Proposed only)	equal to n		equal to $n \times$(1-5)	equal to n
Cyclic Backoff Value $B_C(n)$ (Proposed only)	equal to N		equal to $N \times$(1-5)	equal to N
CW_{min} (DCF, CSMA/ECA)	15			
CW_{max} (DCF, CSMA/ECA)	1023			
User-Oriented QoS Granularity x_q	1			1 and 5

4.4.1. Evaluation 1: Maximum Performance

The evaluation of system throughput, average access delay and average number of retransmissions versus the number of STAs are discussed in this section. In this evaluation, it is assumed that all STAs obey a single scheme; in other words, only one type of STA exists. The system throughput represents the total throughput of N STAs. Fig. 4.11 through Fig. 4.13 shows the simulation results. In the environment with a few STAs, both the CSMA/ECA and the proposed scheme improve throughput as compared to the DCF. On the other hand, the effect of the improvement in the CSMA/ECA is reduced according to the increase in the number of STAs. This is because the CSMA/ECA adopts a random back-off after the first transmission or upon a collision. Therefore, a STA that applies a fixed back-off is forced to apply a random back-off for the next transmission due to a collision with a STA that applies a random back-off. This causes a chain of collisions. Especially if N exceeds CW, a collision is inevitable at the first transmission. Thus, the number of collisions is increased in proportion to the number of STAs.

Conversely, if there is no STA that applies random back-off, the proposed scheme avoids any collisions due to completely centralized operation. Thus, system throughput becomes constant regardless of N. In Fig. 4.11, the proposed scheme achieves a throughput level 70% higher than that for the DCF when N is 50, and a throughput level 40% higher than that for the CSMA/ECA as well. Moreover, as shown in Fig. 4.12, while the CSMA/ECA achieves a reduction of 20% compared to the DCF when N is 50, the proposed scheme reduces the access delay by 40% under the same conditions. Since the proposed scheme excludes any collision, the number of retransmissions of the proposed scheme becomes 0 regardless of N, as shown in Fig. 4.13. On the other hand, the number of retransmissions of the CSMA/ECA is increased because of the chain of collisions described above when the number of STAs exceeds 20 (> CW_{min}). These results confirm the effect of collision avoidance of the proposed scheme and reduction in the overhead time due to pseudo-centralized control.

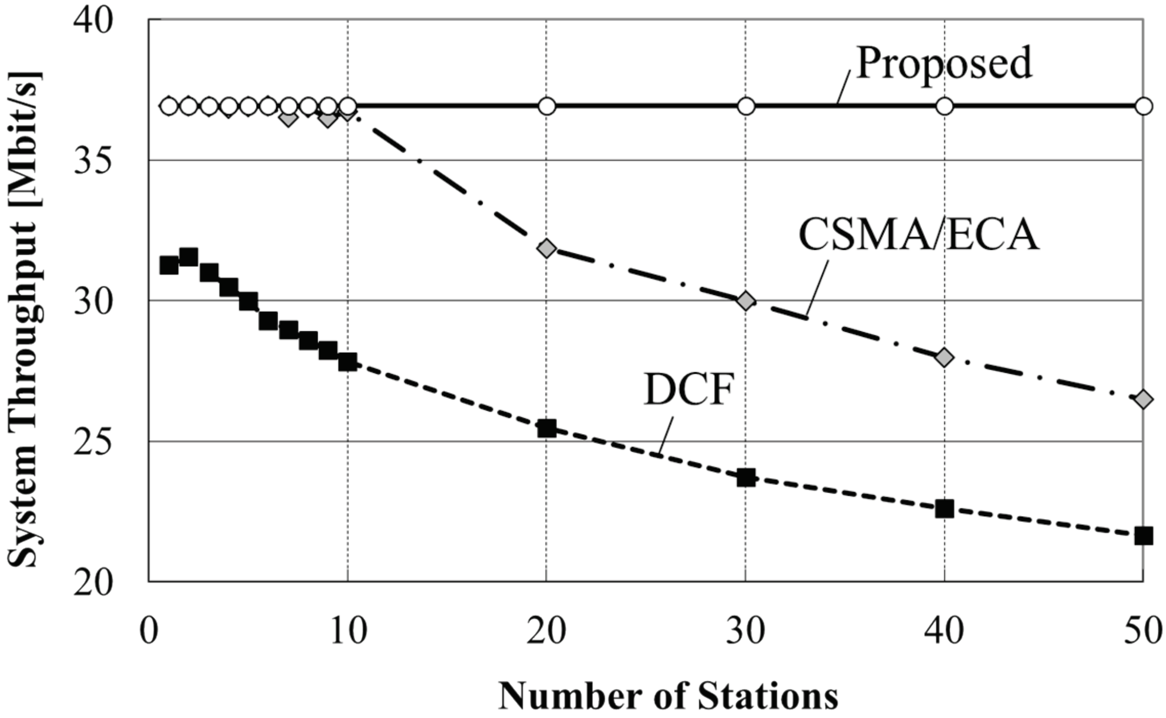

Fig. 4.11 System throughput vs. number of STAs.

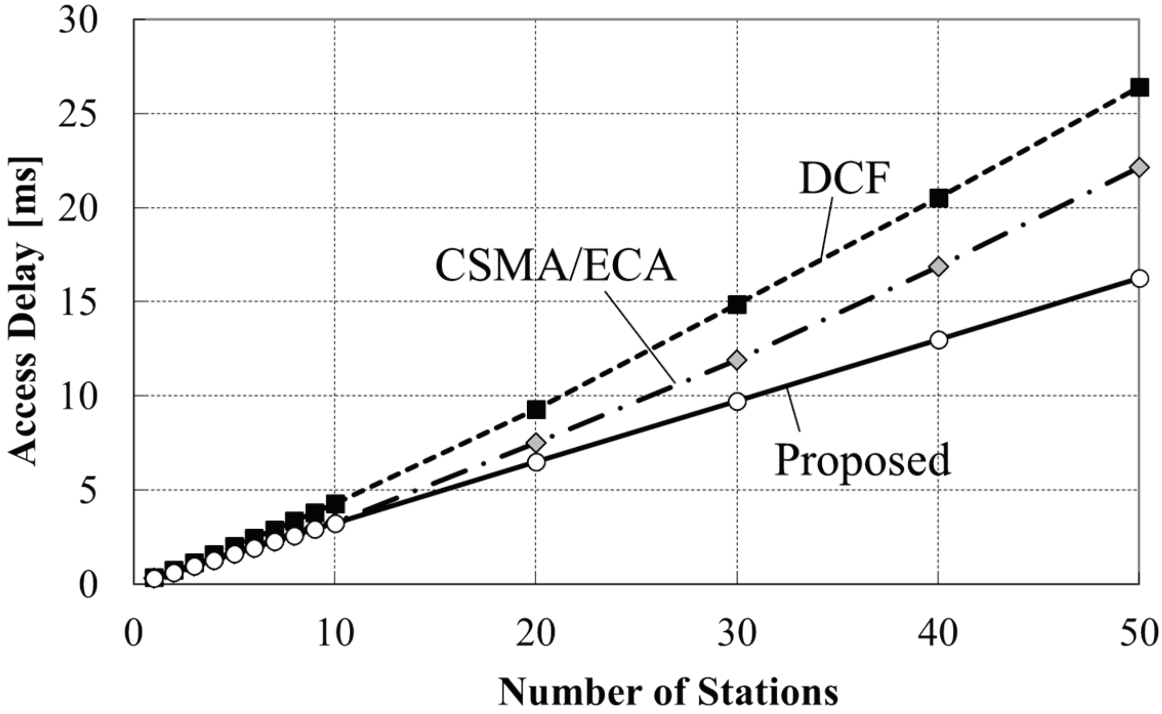

Fig. 4.12 Access delay vs. number of STAs.

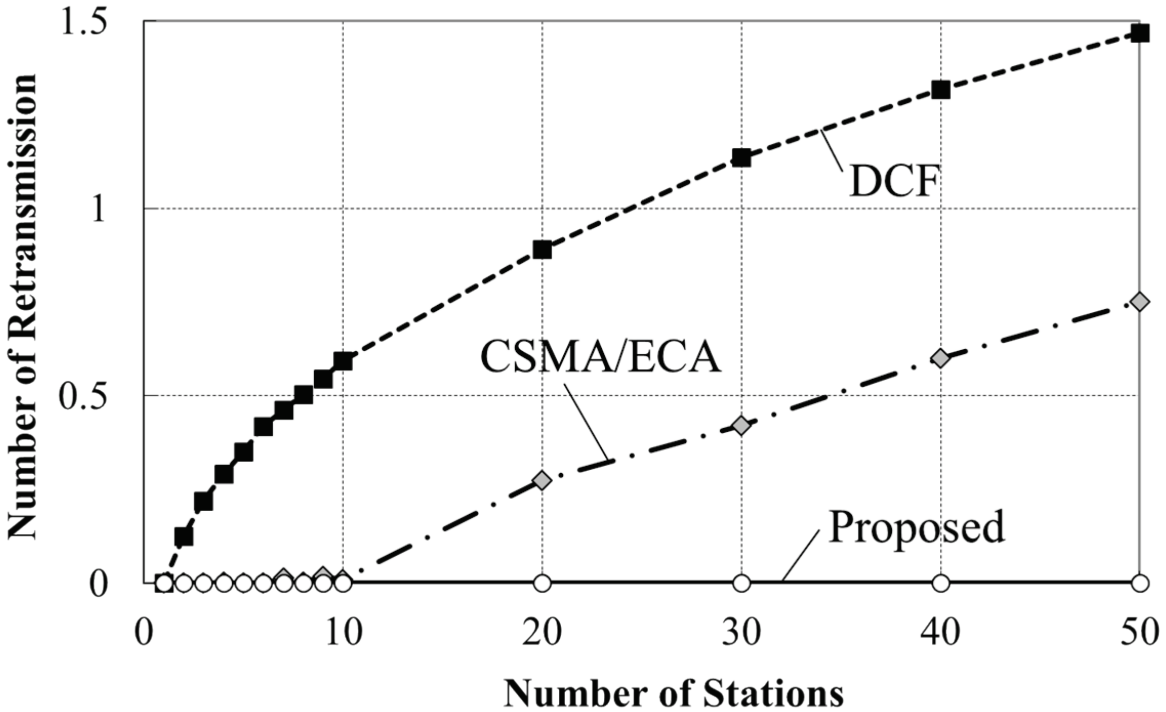

Fig. 4.13 Number of retransmissions vs. number of STAs.

4.4.2. Evaluation 2: Performance in Environment with Coexisting Proposed and DCF STAs (Verification of S-QoS Control)

To verify the effect of controlling the priority level between the proposed scheme and the DCF (S-QoS), the average throughput characteristics are evaluated. An environment where proposed STAs and DCF STAs coexist is assumed in this evaluation. The average throughput of N_p for proposed STAs and that of N_c for DCF STAs are evaluated. The total average throughput of N is measured as well.

First, to confirm the influence of IBV, each IBV is assigned in ascending order and descending order, as expressed in Eqs. (4.4) and (4.5), respectively. Fig. 4.14 shows the simulation results when the proposed STAs are prioritized (ascending IBVs), and Fig. 4.15 shows the results when the DCF STAs are prioritized (descending IBVs). Hereafter, α_q is defined as the ratio of proposed STAs to N. Terms N_p, N_c, and α_q have the following relationships,

$$N = N_p + N_c, \tag{4.9}$$

and

$$N_p = N \times \alpha_q. \tag{4.10}$$

According to the results shown in Fig. 4.14, the total average throughput of N is increased in proportion to α_q. For instance, when α_q = 0.3, the throughput is approximately 10% higher than at α_q = 0. This is because the probability of collision decreases for the entire system as the number of proposed STAs increases. At this time, the proposed STAs gain 160% higher throughput compared to the case where all STAs are DCF STAs (the case where the proposed scheme is not introduced). However, the DCF STAs suffer 50% lower throughput in this case as well. Similarly at α_q = 0.1, the proposed STAs can obtain up to 300% higher throughput and the DCF STAs suffer 40% lower throughput. This is trade-off for setting a higher priority for the proposed STAs. As described in Subsection 4.3.3, the priority of the DCF STAs can be improved at the expense of the proposed STAs by setting larger IBVs. In addition, the average throughput of the proposed STAs is decreased in proportion to α_q. The reason for this is described hereafter. If there are only a few proposed STAs, each proposed STA is likely to collide with a DCF STA. As the proposed STAs reset their back-off value to the IBV when collision occurs, the proposed STAs obtain a chance for transmission by priority. On the other hand, if there are many proposed STAs, their average throughput decreases because all the proposed STAs have higher priority and must share a common resource. In the case where the DCF STAs are given priority, the system throughput is approximately 5% higher at α_q = 0.3 than at α_q = 0, according to the results shown in Fig. 4.15. This implies that the improvement in the system throughput is lower than that in the case where the proposed STAs are given priority. The reason for this is that the number of chances for transmission for the proposed STAs is reduced and the effect of collision avoidance becomes smaller than that for the case in which the proposed STAs are given priority. At this time, the DCF STAs gain 40% higher throughput compared to the case in which all STAs are DCF STAs. On the other hand, the proposed STAs suffer 80% lower throughput in this case for the same reason described above.

Second, to verify the impact of CBV on the S-QoS, the average throughput of each scheme is evaluated. In this evaluation, it is assumed that $\alpha_q = 0.5$ and $B_I(n)$ is arranged in ascending order, as expressed in Eq. (4.4) to give priority to the proposed STAs first. Then, B_c is escalated gradually shift to the priority to DCF STAs. Fig. 4.16 shows the simulation results. The results indicate that increasing the CBV can give priority to the DCF STAs while suppressing the deterioration of the system throughput. Specifically, the total average throughput of N is reduced by only 10% for $B_c = 250$, as compared to when $B_c = 50$ and the priority between the proposed STAs and DCF STAs becomes reversed.

Last, a performance comparison between the proposed scheme and the CSMA/ECA in an environment where proposed STAs and DCF STAs coexist is verified. Fig. 4.17 shows the total average throughput of N versus α_q, which indicates the proportion of proposed STAs or the CSMA/ECA STAs to N. According to the results in Fig. 4.17, the proposed scheme achieves better performance than the CSMA/ECA at any α_q. This is because collisions between the proposed STAs are avoided by designating a fixed back-off. By contrast, collisions between the CSMA/ECA STAs cannot be eliminated because of the random back-off, as described in Subsection 4.2.

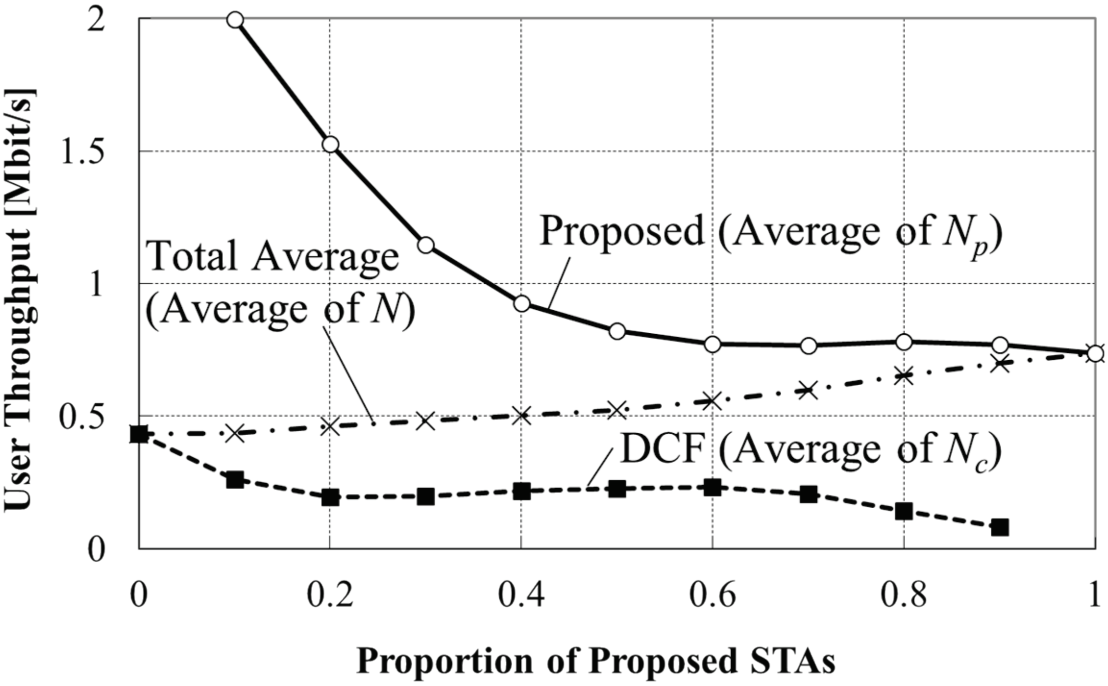

Fig. 4.14 Performance in coexistence environment (Proposed prioritization).

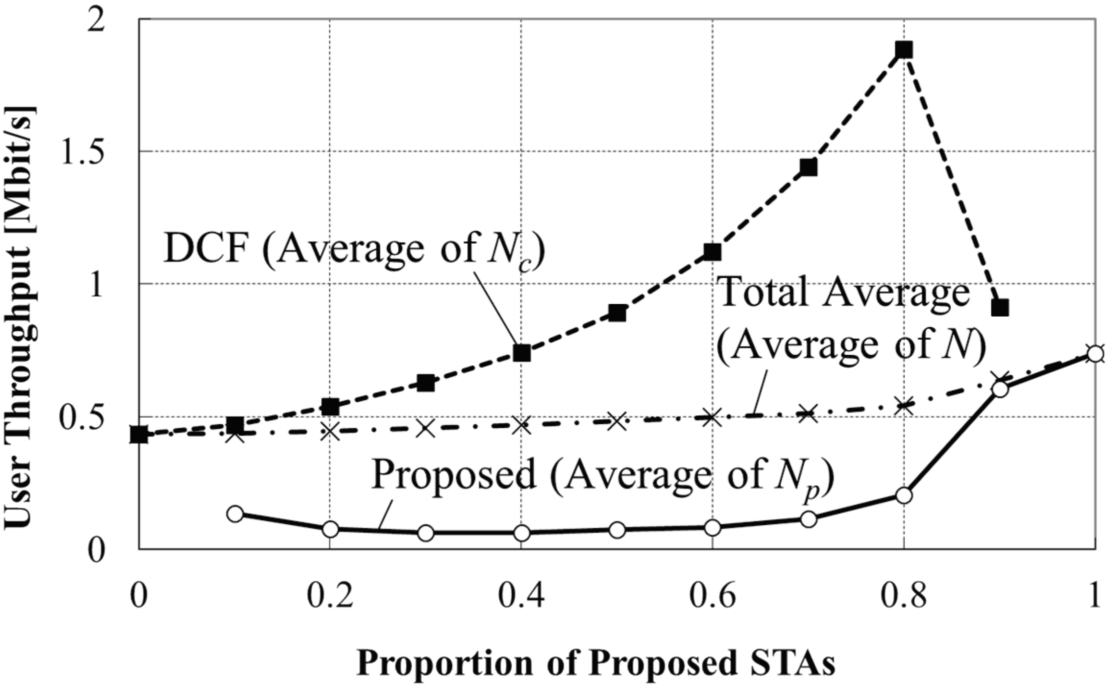

Fig. 4.15 Performance in coexistence environment (DCF prioritization).

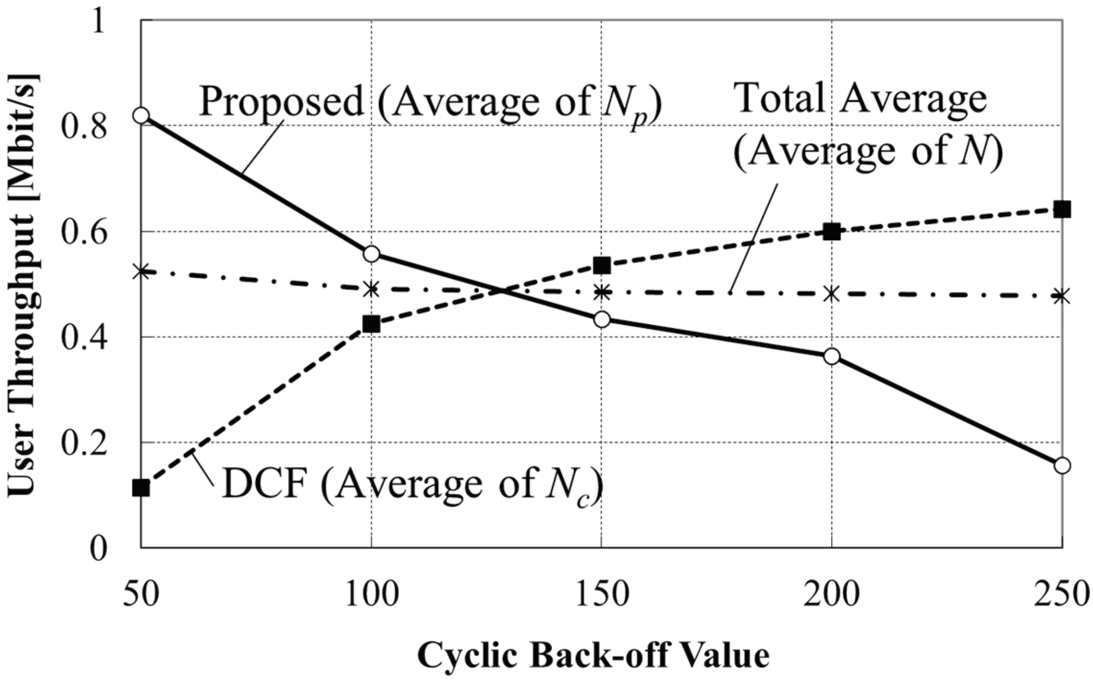

Fig. 4.16 S-QoS control using CBV.

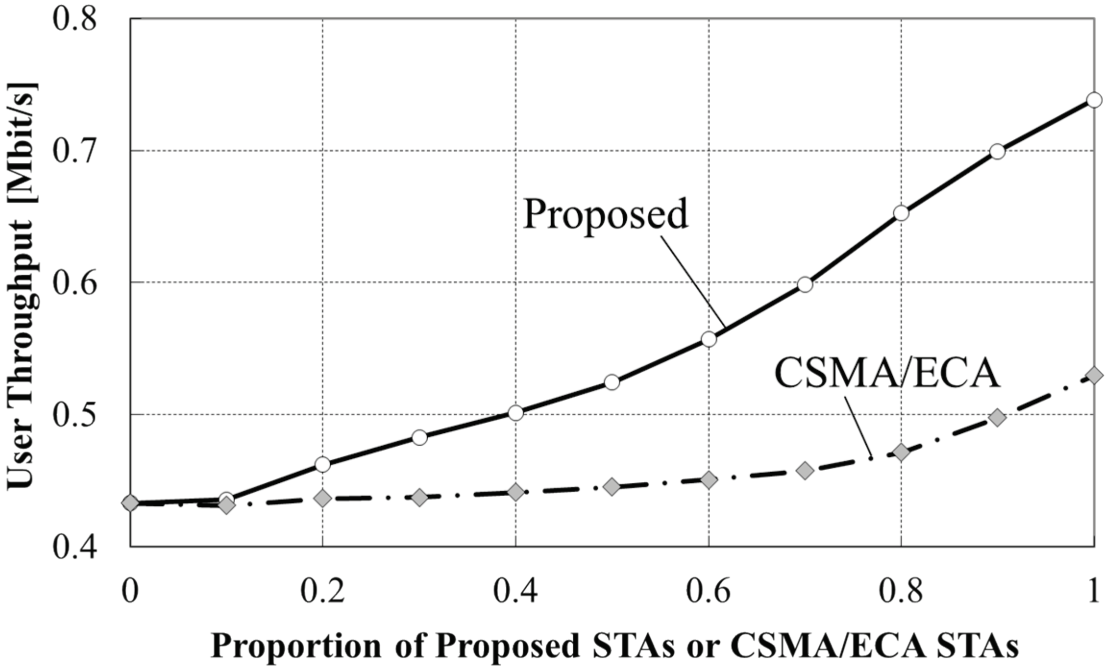

Fig. 4.17 Performance in coexistence environment (Proposed scheme vs. CSMA/ECA).

4.4.3. Evaluation 3: Performance in Environment with Coexisting Proposed and DCF STAs (Verification of U-QoS Control)

In this subsection, the effect of controlling the U-QoS is evaluated. Each $B_I\,(n)$ is arranged in ascending order as expressed in Eq. (4.4), and two kinds of QoS classes are introduced. The classification of the QoS is executed according to Eq. (4.7); One experiment has five QoS classes (x_q = 5), and the other has no QoS classes (x_q = 1, impartial). In addition, it is assumed that α_q = 0.3 and compared the case in which the proposed STAs are classified by QoS classes, and the case in which all STAs are the DCF (α_q = 0).

Fig. 4.18 shows the throughput achieved by each STA. In Fig. 4.18, the STA number n_p, is represented on the horizontal axis. In the case of x_q = 5, the throughput characteristics are quantized to five QoS classes according to the results. In this simulation, the STAs numbered 1, 6, and 11 achieve the highest throughput. This is because the $B_I\,(n)$ values of these STAs change in the rotation into only three values, namely 1, 6 and 11, according to Eq. (4.7). The STAs that obtain the second highest throughput levels are numbers 2, 7, and 12, for the same reason described above. The $B_I\,(n)$ of these STAs also holds only three values. Moreover, the rest of the STAs comply in the same manner and are classified into each QoS class.

In addition, the results indicate that the throughput characteristic become equal in the case of x_q = 1. In this case, each $B_I\,(n)$ value from all the proposed STAs is assigned from 1 to 15 in turn to eliminate the difference in priority among the proposed STAs. Moreover, the throughput of all the proposed STAs is superior to that of the DCF STA. Therefore, it is clarified that the U-QoS control is achieved by setting an appropriate IBV in turn.

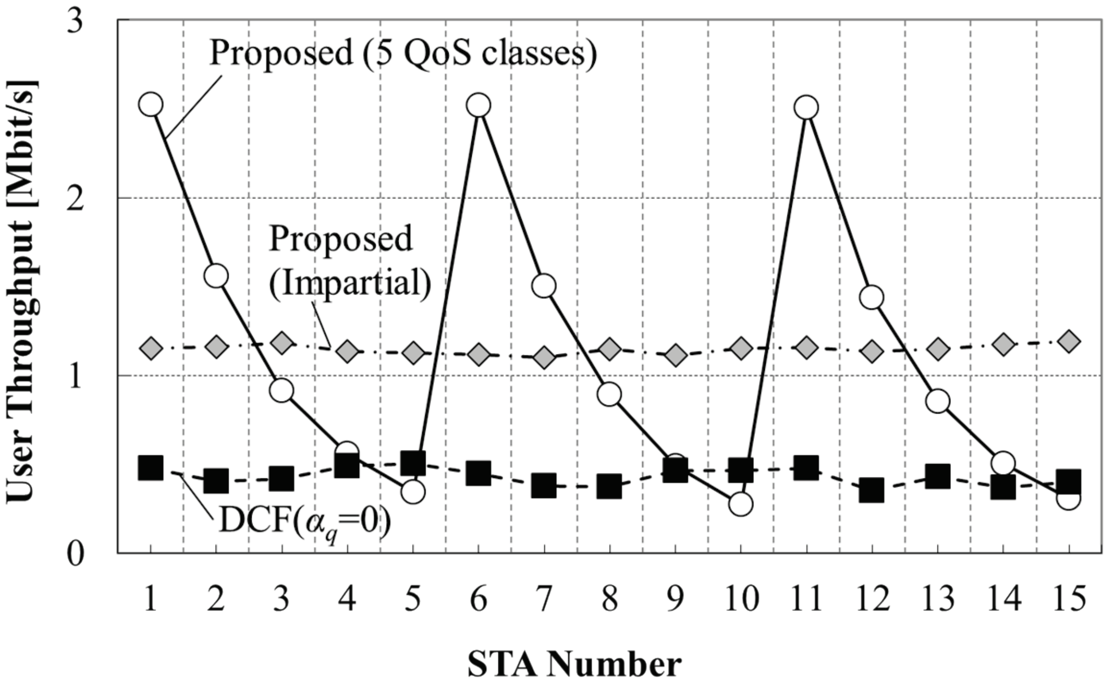

Fig. 4.18 U-QoS control using IBV.

4.5. Summary

In this chapter, a pseudo-centralized control scheme based on the CSMA/CA was proposed. The proposed scheme suppresses collisions between proposed STAs, improves the throughput characteristics and shortens the access delay. Moreover, the proposed scheme controls the user-oriented QoS by setting two kinds of fixed back-off values, namely, the IBV and CBV. If a low number is assigned to the IBV, the priority of the proposed STA increases, and vice versa. Conversely, increasing the CBV increases the priority level of the DCF STAs. In addition, the granularity of the user-oriented QoS classes can be specified by setting the appropriate IBVs. These effects are verified through computer simulations. Thus, the proposed scheme is highly effective in protecting the user-oriented QoS in a congested situation with many WLAN STAs. The results of computer simulations showed that the proposed scheme can achieve up to over 300% higher user throughput, compared to the case in which the proposed scheme is not introduced under the coexistence environment with DCF STAs. In addition, all the proposed STAs achieved 70% higher throughput than the DCF STAs under a non-coexistence environment.

Future research will include negotiation with neighbor-proposed APs and assignment of adequate IBVs by considering STAs connected to the neighboring APs. Moreover, although I am convinced that the hidden terminal problem can be overcome by using the Request-To-Send (RTS) / Clear-To-Send (CTS) procedure in the proposed scheme, evaluations considering the problem should be introduced analytically in future research because unconformity in the IBV for proposed STAs breaks the pseudo-centralized control and degrades the throughput characteristics.

I consider that the proposed scheme can be improved to enable control of not only user-oriented QoS but also application-oriented QoS. In future research, I plan to investigate in detail the queuing mechanism to achieve application-oriented QoS control.

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Chapter 5

Interference Avoidance Scheme for Wireless Mobile Routers

5. Interference Avoidance Scheme for Wireless Mobile Routers

5.1. Introduction

As described in Chapter 1, WLAN devices that comply with the IEEE 802.11 standard [5.1] are widely implemented in various mobile terminals not only laptop PCs but also small multimedia devices such as music players, gaming machines, and smart phones. Demand has been growing that these mobile terminals be usable everywhere. However, WLAN service areas are restricted to WLAN hotspots in public areas. In order to solve this problem, wireless mobile routers, which can connect WLAN terminals to the backbone network by using other wireless system with wide communication area, are a hot research topic [5.2]-[5.4]. On the other hand, WiMAX that complies with the IEEE 802.16 [5.5] has received a lot of attention due to its potential in terms of wide communication area and high-speed data transmission. In particular, mobile WiMAX based on the IEEE 802.16e [5.6] is a very attractive system for mobile use, because mobile WiMAX provides the high speed transmission for mobile users. The wireless mobile router has the functions of WLAN AP and of WiMAX MS. The WLAN STAs are connected to the AP in the wireless mobile router via an 802.11 link. Hence, the wireless mobile router converts media between the IEEE 802.11 and IEEE 802.16e. This fact enables the WLAN STAs to connect to the backbone IP network. However, the chassis of the wireless mobile router must be downsized because it is assumed to be carried in outdoor. Therefore WLAN and WiMAX devices are required to be installed next to each other in these wireless mobile routers. Moreover, the assigned frequency bands of WLAN and WiMAX are 2.4 and 2.5 GHz, respectively. This situation triggers mutual system interference between the two wireless devices and system throughput of the wireless relay is greatly degraded [5.7].

There are a lot of prior studies concerning wireless mobile routers that use WLANs and WiMAX [5.8]-[5.11], however, they concentrated on handover between WLAN and WiMAX. On the other hand, prior studies [5.12]-[5.14] proposed a resource management method for a hybrid network that bridged WLAN and WiMAX. However, the problem concerning mutual system interference was not considered. Although Refs. [5.15], [5.16] analyzed the effect of mutual system interference in a heterogeneous network of WLAN, Bluetooth and / or WiMAX in detail, no interference avoidance technique was introduced. There are a lot of schemes that can suppress interference in the PHY layer [5.17]; however, hardware modification of existing WLAN terminals is required and signal processing is complex when using the interference suppression.

Therefore, this chapter proposes a novel interference avoidance technique that achieves a simple implementation using only MAC protocol. The proposed scheme synchronizes the transmission and the reception timing of WiMAX and WLAN and avoids the case where interference is generated in the wireless mobile router. Mutual system interference is generated when WiMAX device of Wide Area Network (WAN) transmits signals while WLAN device of Local Area Network (LAN) receives signals. In the case when WLAN transmits signals while WiMAX receives signals, mutual system interference is generated in the same way. Ordinarily, it is difficult to synchronize transmission and reception timing of WLAN with WiMAX because the CSMA/CA adapted to the IEEE 802.11 WLAN systems is based on the random access procedure. On the other hand, the PSMP is regulated in order to save power consumption of WLAN as described in Chapter 2. The PSMP easily allows WLAN AP to control the transmission and reception timing of STAs. Hence, the proposed scheme enables interference avoidance between WLAN and WiMAX by applying the PSMP.

5.2. Mutual System Interference between WLAN and WiMAX

This subsection describes the condition that the mutual system interference is generated and the experiments conducted to verify the issue raised by the mutual system interference between WLAN and WiMAX.

Fig. 5.1 and Fig. 5.2 illustrate the concept of WLAN-WiMAX relay via the wireless mobile router and simplified configuration of the wireless mobile router respectively. Wireless mobile routers are expected to implement wireless devices into a size that is smaller than the business card. Therefore, the devices of WLAN and WiMAX are located at adjacent spaces, respectively. In addition to the condition, the emission of the spectrum mask leaks outside the band and caused mutual system interference when the frequency band of WLAN and WiMAX is adjacent. Fig. 5.3 shows this problem conceptually. Here, it is assumed that the issue of mutual system interference generated in the circuit in the wireless mobile router is another problem for the future work. In this dissertation, I concentrate on the issue of mutual system interference caused in the air.

To verify this problem practically, the experiments using WLAN AP, STA, WiMAX BS and MS are conducted. Fig. 5.4 illustrates the block diagram of mutual system interference of the experiments. The experiments focus on the throughputs of WLAN and WiMAX. In order to precisely observe the power degradation caused by mutual system interference, wired links with the same attenuators are used as wireless links. That is, the attenuators degrade signal power by an amount equal to the free-space path loss yielded by the distance between wireless devices; fading is not considered in the experimental system. The parameters of the experiments are shown in Table 5.1. Besides, the standards of WLAN and WiMAX comply with the IEEE 802.11g and the IEEE 802.16e respectively. The throughput characteristics of WiMAX and of WLAN are shown in Fig. 5.5 and Fig. 5.6, respectively. Fig. 5.5 indicates that the downlink (DL) throughput of WiMAX began to degrade when the distance between WLAN AP and WiMAX MS were 10 cm apart, the downlink throughput halved at 5 cm, and connection lost at approximately 1 cm. Fig. 5.7 illustrates the waveform of interference WLAN signals and desired WiMAX signals that observed at 1 cm distance. In the observation point, WiMAX MS is receiving DL Burst while WLAN AP is transmitting signals for WLAN STA. Point "A" in Fig. 5.4 is the probe point of this waveform. From Fig. 5.7, desired WiMAX signal is almost buried in the emission of undesired WLAN signal. Therefore, it is clear that WLAN interference degrades WiMAX throughput. Fig. 5.6 also indicates that WLAN uplink (UL) throughput began to degrade at the separation distance of 32 cm; a 70% throughput reduction occurred at 5 cm. Fig. 5.8 illustrates the waveform of desired WLAN signals and interference WiMAX signals that observed at 1 cm distance. In the observation point, WLAN AP is receiving signals from WLAN STA while WiMAX MS is transmitting UL Burst. Point "B" in Fig. 5.4 is the probe point of this waveform. As well as Fig. 5.7, Fig. 5.8 indicates that desired WLAN signal severely disturbed from the emission of undesired WiMAX signal. Therefore, WiMAX interference degrades WLAN throughput in both the uplink and downlink. The reason why not only WLAN UL throughput but also WLAN DL throughput decreases is as follows; When WLAN STA receives the signal correctly from WLAN AP, WLAN STA casts an ACK frame to WLAN AP. This ACK frame is carried in a signal sent in the WLAN UL direction. Therefore, this ACK frame is affected by the mutual system interference from WiMAX UL signals. The throughput of WLAN DL decreases as a result so that WLAN AP, which was not able to receive ACK frames properly resends, DL signals to WLAN STA. Moreover, WLAN AP transmission was halted due to the carrier sense function which uses the CSMA/CA.

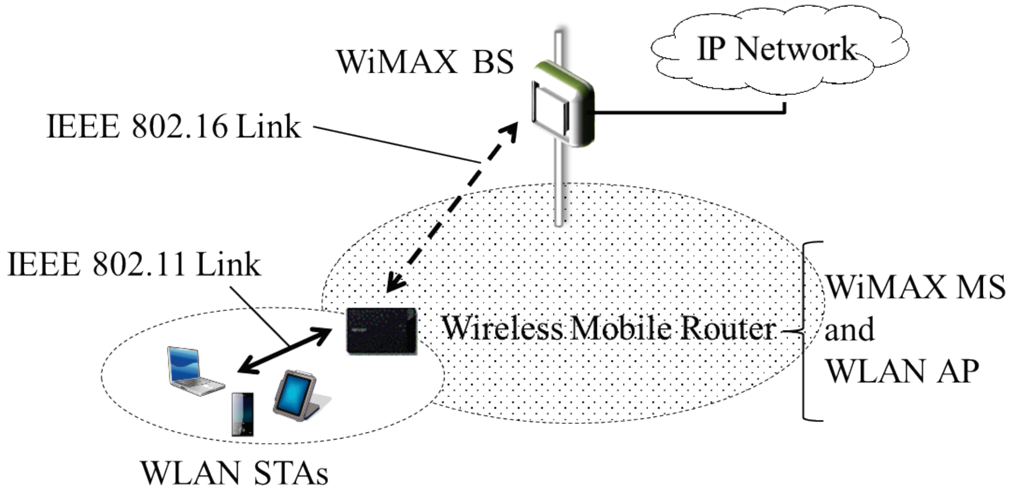

Fig. 5.1 Concept of WLAN-WiMAX relay via wireless mobile router.

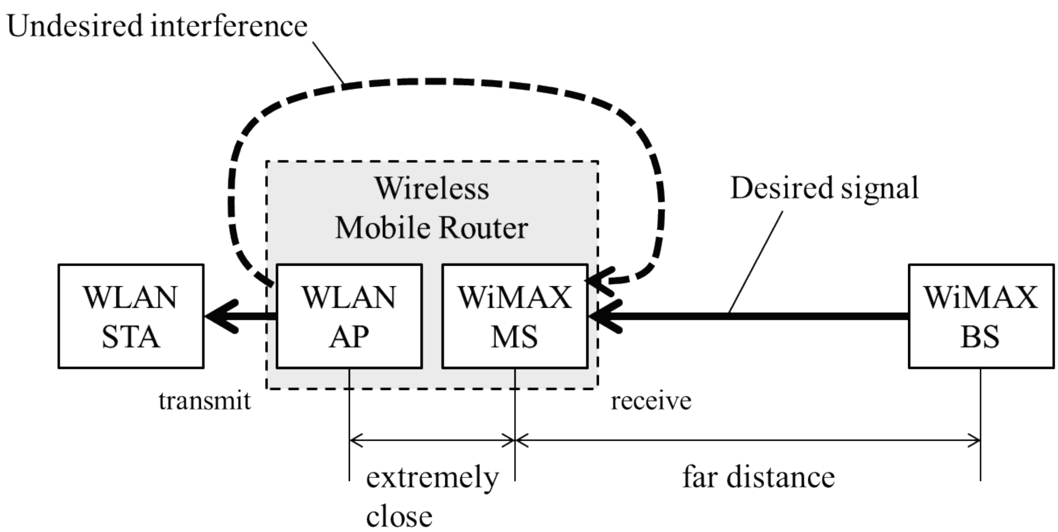

Fig. 5.2 Simplified configuration of wireless mobile router.

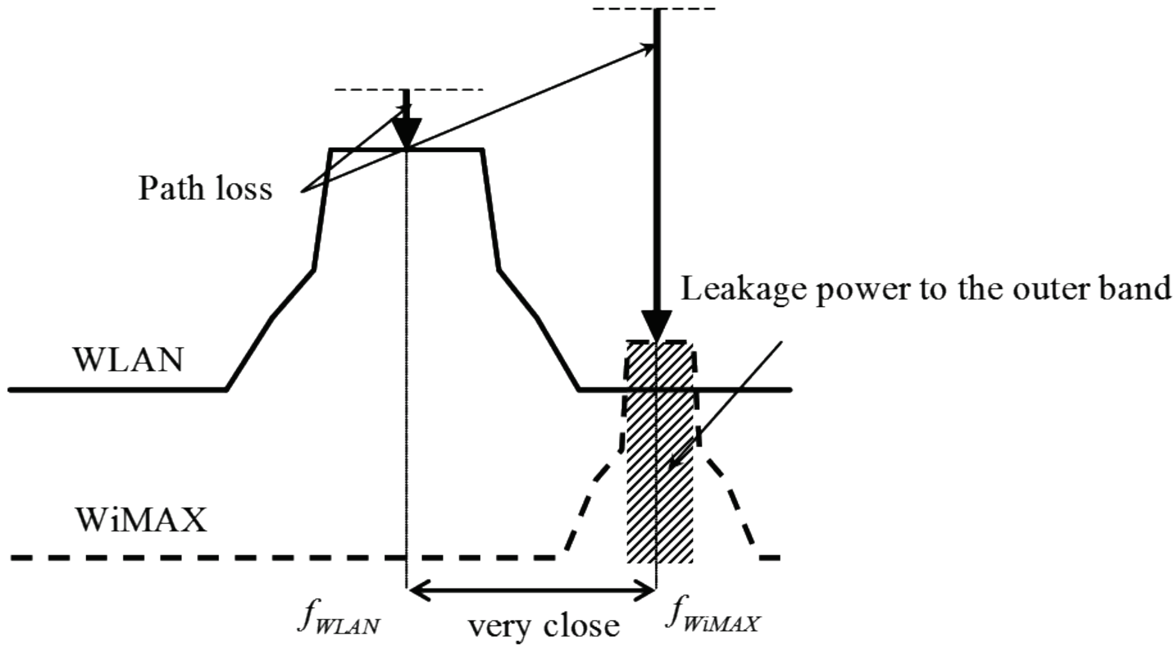

Fig. 5.3 The concept of mutual system interference.

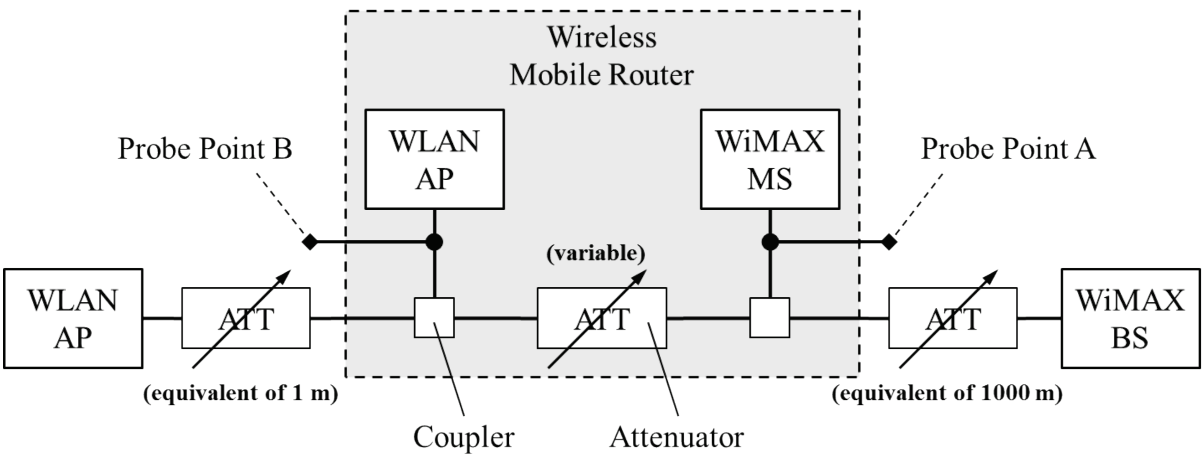

Fig. 5.4 Block diagram of experiments.

Table 5.1 Experimental parameters.

Parameter	Value
Tx Power of WLAN AP [dBm]	20
Tx Power of WLAN STA [dBm]	20
Tx Power of WiMAX BS [dBm]	45
Tx Power of WiMAX MS [dBm]	27
Distance beween WLAN STA and WLAN STA [m]	1
Distance beween WiMAX MS and WiMAX BS [m]	1000
Distance beween WLAN AP and WiMAX MS [m]	0.01-0.6
WiMAX Scheduling Type	UGS
WiMAX DL/UL Ratio	1
WiMAX DL Maximum Received Traffic Rate [Mbit/s]	2
WiMAX UL Maximum Received Traffic Rate [Mbit/s]	1

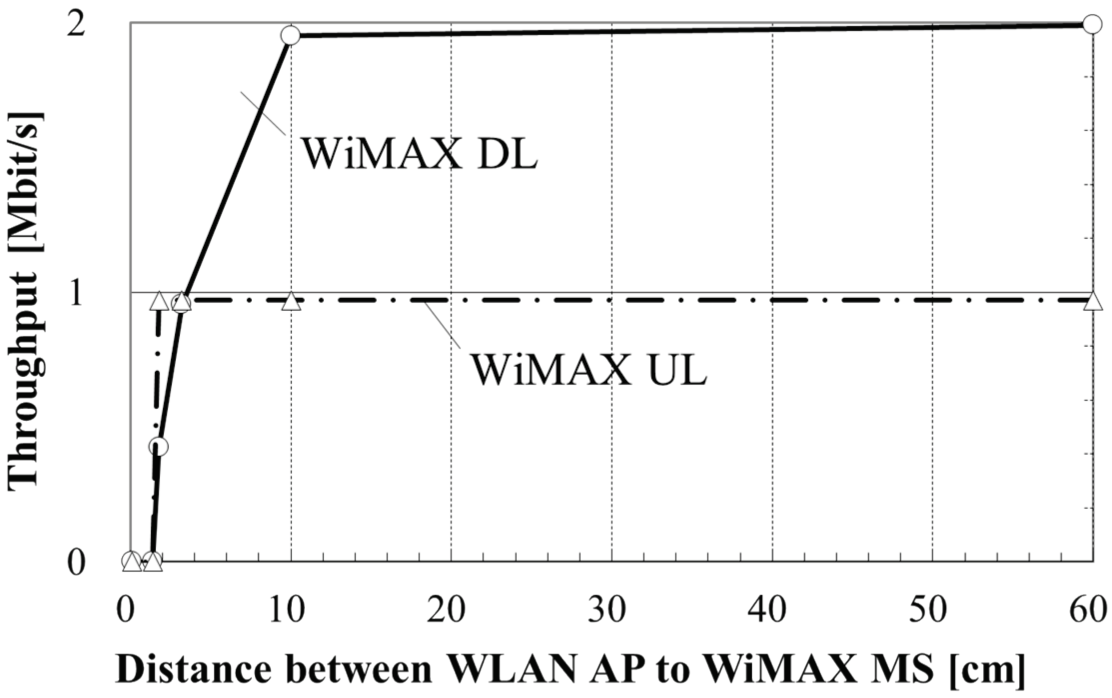

Fig. 5.5 Uplink / Downlink throughput of WiMAX.

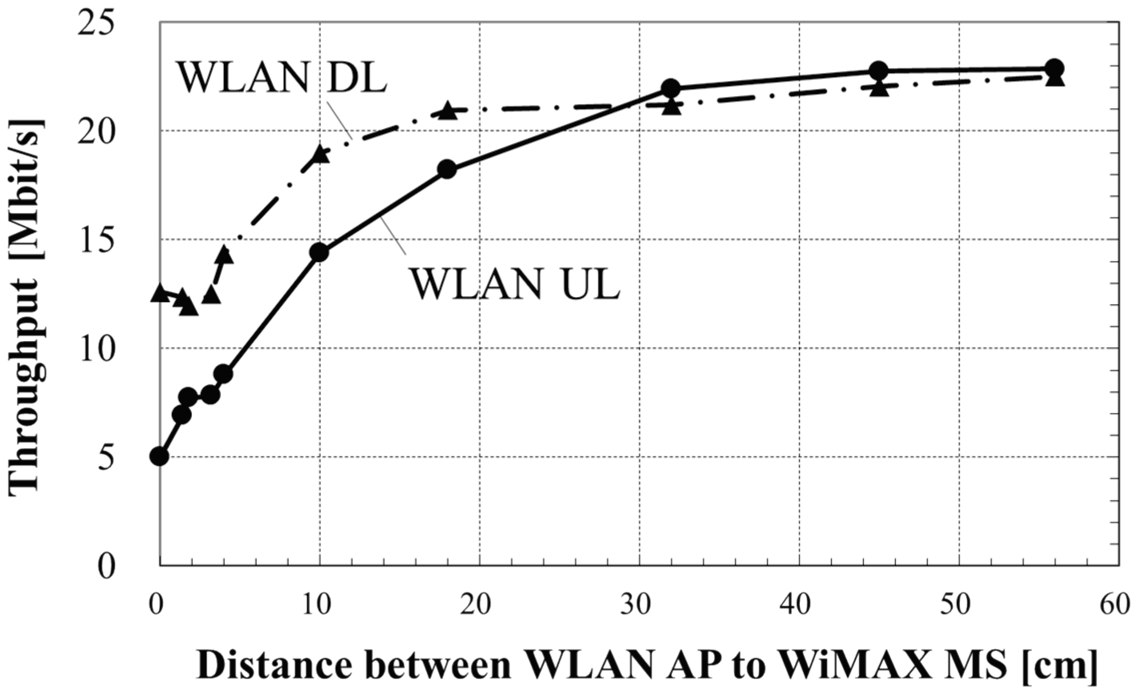

Fig. 5.6 Uplink / Downlink throughput of WLAN.

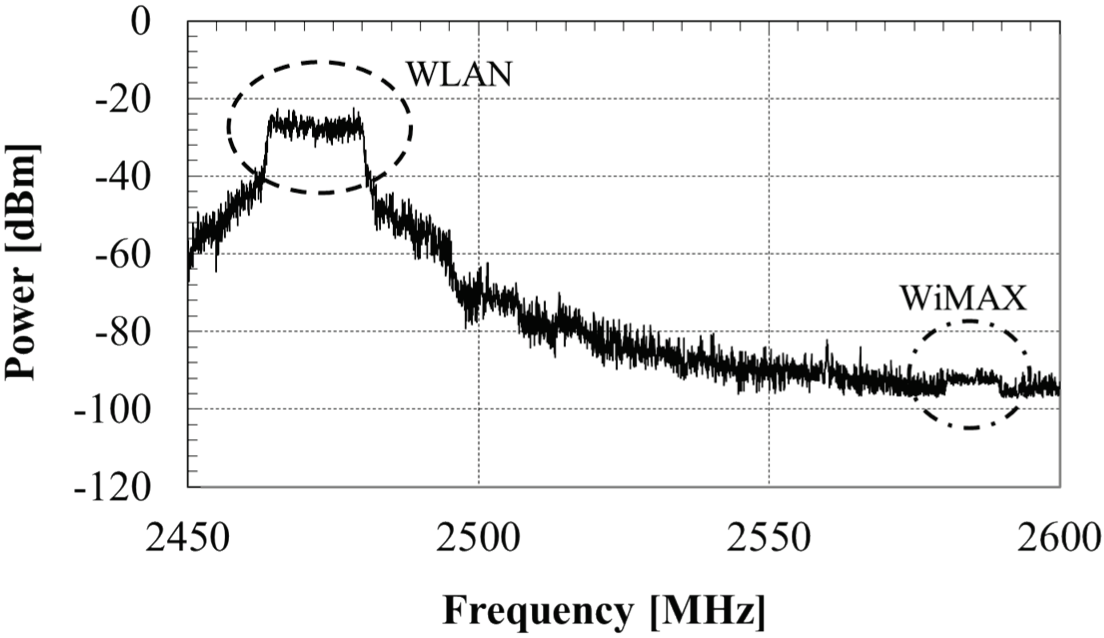

Fig. 5.7 Waveform of WLAN and WiMAX signals in downlink.

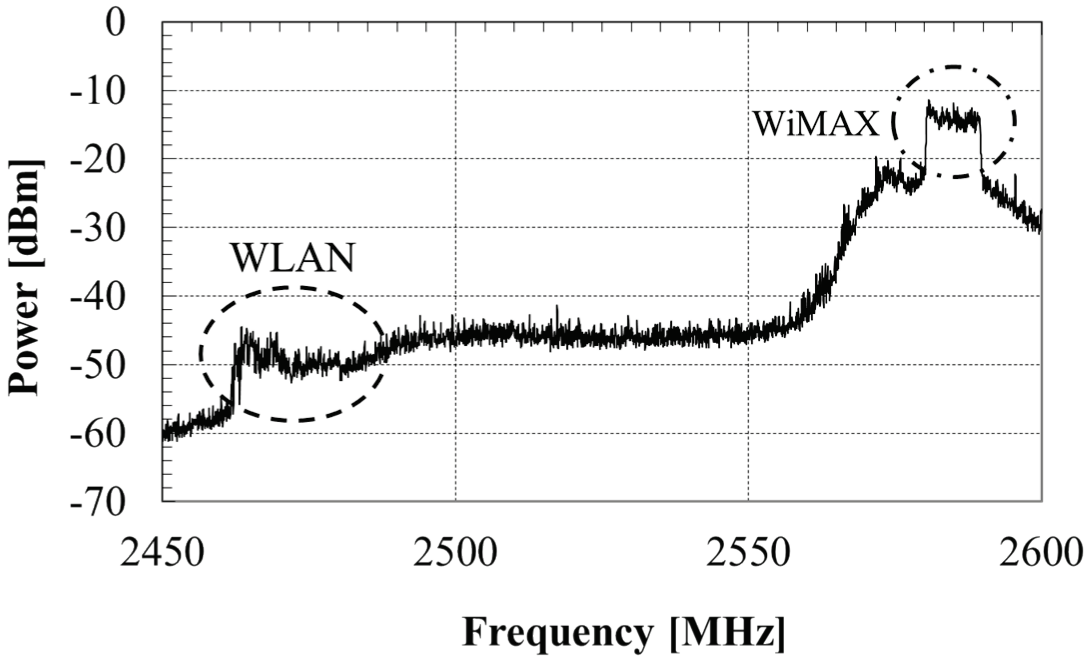

Fig. 5.8 Waveform of WLAN and WiMAX signals in uplink.

5.3. Conventional Operations for Wireless Mobile Router

This subsection introduces conventional operation and interference avoidance scheme for wireless mobile routers and their issues. The conventional MAC protocol procedures are detailed below.

In the conventional operation, WLAN and WiMAX perform their normal transmission sequences independently. This scheme is defined as Autonomous Distributed Control (ADC) as shown in Fig. 5.9. In the ADC, no synchronization between WLAN and WiMAX is performed. Although the conventional scheme using the ADC is simple, mutual system interference occurs if one of the wireless devices in the wireless mobile router is receiving signals while the other is transmitting signals. Particularly if mutual system interference occurs while receiving WiMAX control signals such as preamble, FCH (Frame Control Header), DL-MAP and UL-MAP, throughput is severely degraded by the corruption of entire WiMAX frames. Therefore, to avoid this mutual system interference, a scheme by which WLAN and WiMAX can coexist, is being discussed [5.18] in the WiMAX Forum [5.19]. That scheme leverages the sleep mode function specified in the IEEE 802.16e. In the sleep mode, WiMAX BS divides the transmission period into sleeping period and listening period. Listening period is the time for normal transmission, and the sleeping period halts all transmission to cut WiMAX MS power consumption. In this scheme, WLAN AP executes its normal transmission during WiMAX sleeping period, on the other hand, all WLAN devices refrain from transmission during the WiMAX listening period as shown in Fig. 5.10. This scheme is defined as Time Division Duplex (TDD) and it prevents mutual system interference. However, it halves the throughput of each wireless system because each system can utilize only half of period for transmission.

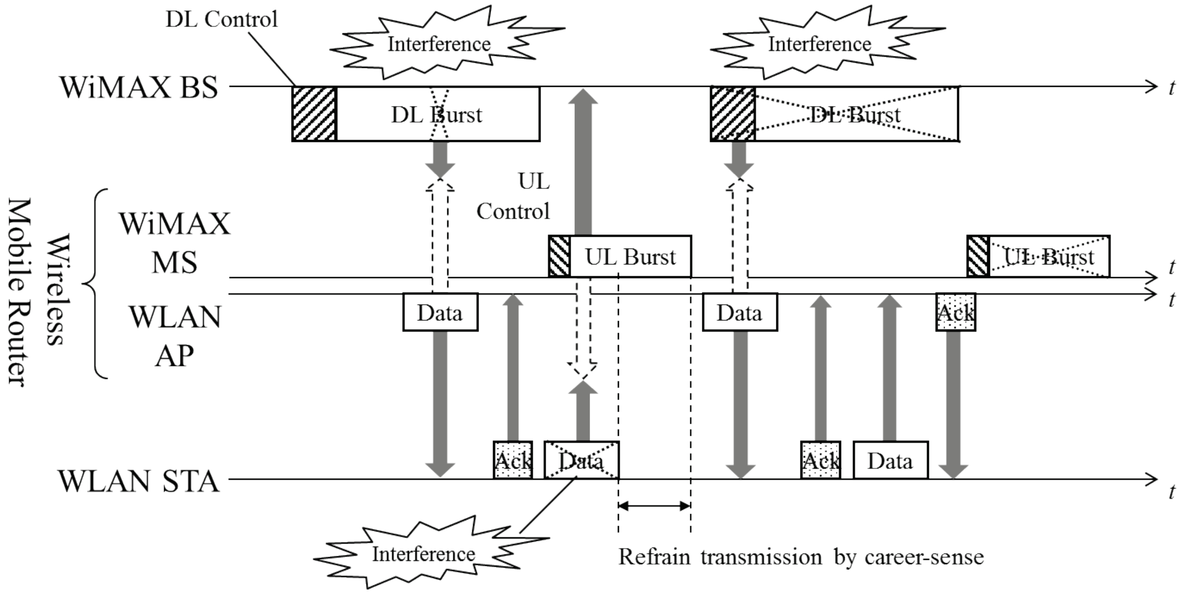

Fig. 5.9 Operation of Conventional ADC.

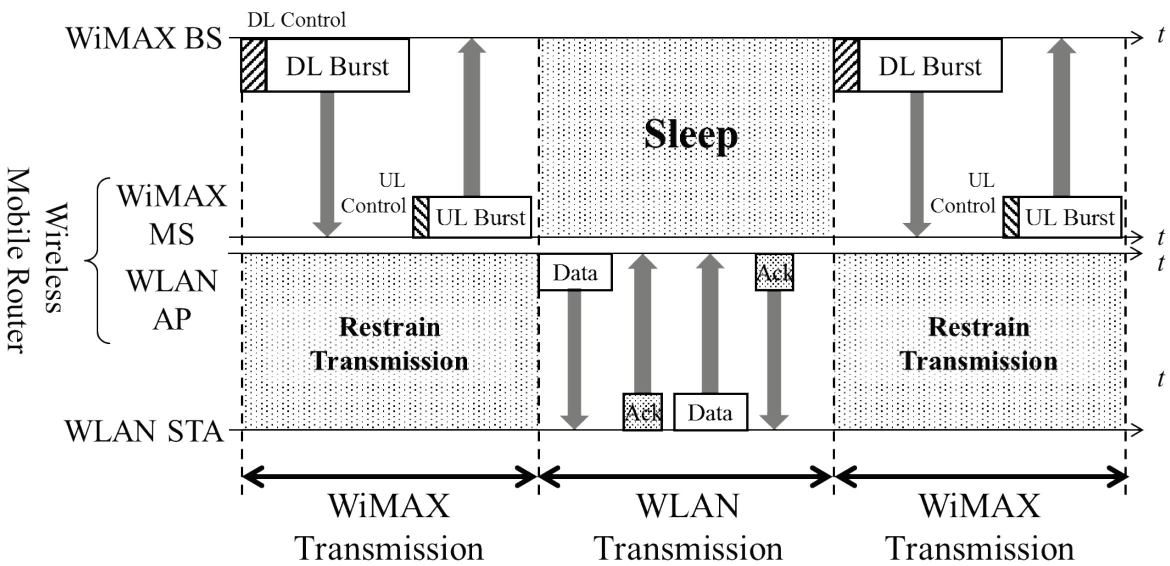

Fig. 5.10 Operation of Conventional TDD.

5.4. Proposed Scheme

In this section, mutual system interference avoidance scheme by scheduling of transmission for WLAN systems is proposed. The proposed scheme leverages the PSMP function specified in the IEEE 802.11 [5.1] as described in Chapter 2. The PSMP is designed for WLAN STA power saving; however I utilize the PSMP for interference avoidance and the proposed scheme improves the throughput characteristics of WLAN-WiMAX relay. The basic idea is described in Subsection 5.4.1. The mechanism of scheduling that optimizes bandwidth allocation for both WiMAX and WLAN systems is described in Subsection 5.4.2. The details of the theoretical calculation of the proposed scheme are explained in Subsection 5.4.3.

5.4.1. Basic Operation

The basic access mechanism of the proposed scheme is illustrated in Fig. 5.11. The concept of the proposed scheme is to make the PSMP sequence as long as a WiMAX frame. That is, the proposed scheme makes the length of WLAN Uplink Phase equal to the length of WiMAX DL Subframe. The length of WLAN Downlink Phase is made equal to the length of WiMAX UL Subframe as well. Accordingly, the basic operation enables the wireless mobile router to transmit signals only in WLAN Downlink Phase, and to receive signals only in WLAN Uplink Phase. That is, the wireless mobile router eliminates mutual system interference which realizes highly effective relay transmission. Although WLAN STAs or APs cannot execute only transmission or reception in a certain period due to the handshake mechanism of an ACK frame, the PSMP function enables that mechanism by indicating the transmission timing for each STA. As described in Chapter 2, WLAN STAs can only receive or transmit signals during assigned period which is indicated by the PSMP frame and ACKs, Block ACKs or MTBAs are sent back in their transmission period.

On the other hand, in the Mobile WiMAX profile [5.19], the ratio of the number of OFDM symbols of DL to that of UL has been decided. According to the profile, the length of DL Subframe is longer than UL Subframe. In Japan and many other countries, the dominant numbers of OFDM Symbols in DL and in UL are set at 32 and 15, respectively. In this chapter, the length of DL Subframe and UL Subframe complies with above system profile. Although the proposed scheme is more effective than the conventional ADC or TDD, system throughput might be degraded by the difference in traffic between WiMAX and WLAN. In other words, the transmitted WLAN traffic might be less than WiMAX traffic because the transmission period of WLAN AP (WLAN Downlink Phase) is limited by the WiMAX UL Subframe period as shown in Fig. 5.12. In Fig. 5.12, the horizontal axis represents time, and the vertical axis means actual transmission rate of each wireless system including loss of overhead (for example, IFS for WLAN, FCH, DL-MAP and UL-MAP for WiMAX).

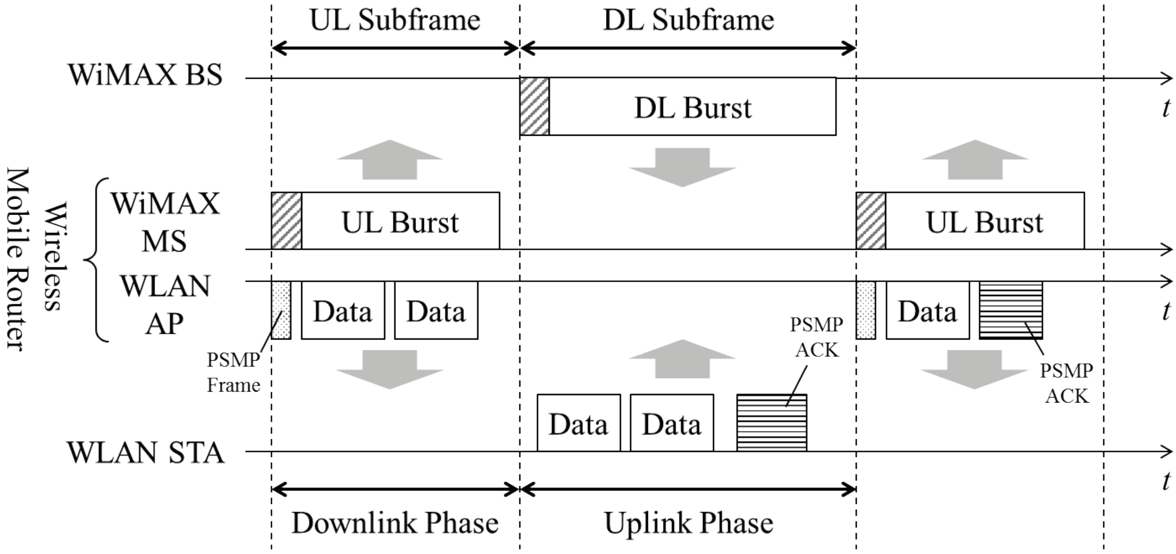

Fig. 5.11 Basic operation of proposed scheme.

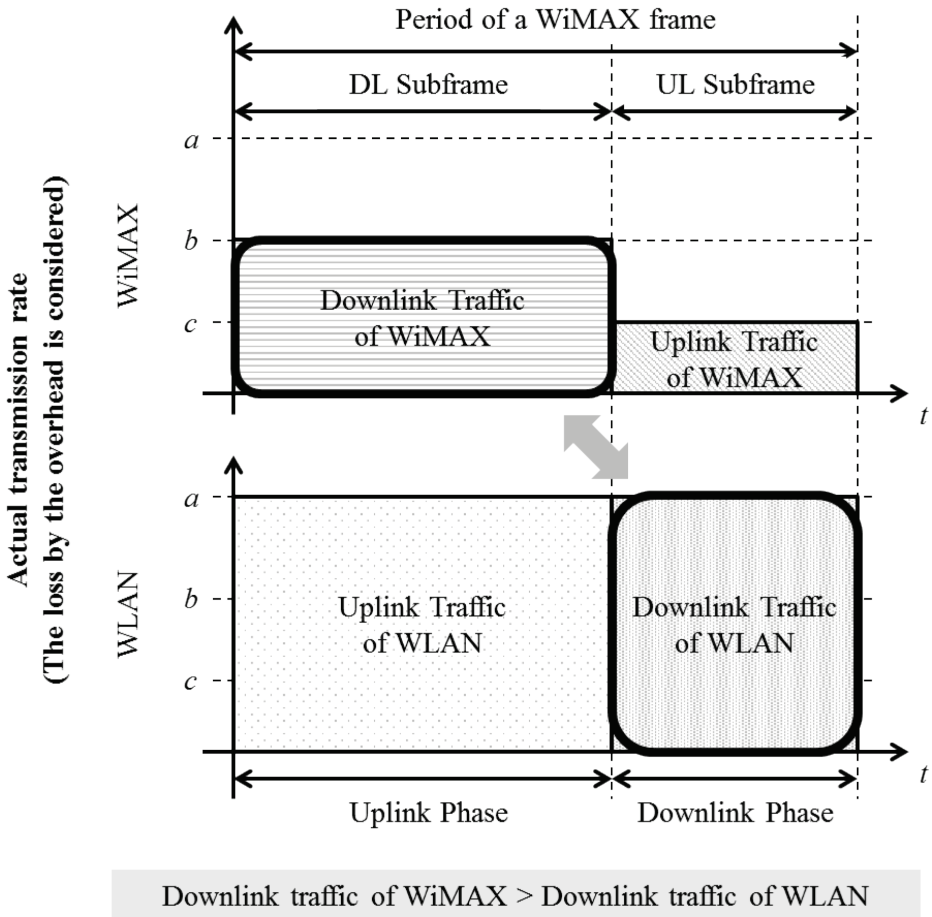

Fig. 5.12 Key issue of basic operation.

5.4.2. Scheduling Method for Bandwidth Optimization

To solve the issue of basic operation raised in Subsection 5.4.1, scheduling scheme is added to the proposed scheme in this subsection. The scheduling scheme modifies the length of WLAN Downlink Phase in order to make the gap of the amount of traffic between WiMAX downlink and WLAN downlink minimum. Firstly, the scheduler expands the WLAN Downlink Phase to match the amount of WLAN downlink traffic and WiMAX downlink traffic as shown in Fig. 5.13. At this time, the wireless mobile router requests WiMAX BS not to allocate WiMAX DL Burst for the wireless mobile router after the beginning of WLAN Downlink Phase using the message of Bandwidth Request Header. The reasons for this are that the WiMAX DL Burst and the transmission in WLAN Downlink Phase after the period might trigger mutual system interference. Secondly, as well as the downlink scheduling, the optimal length for WLAN Uplink Phase is decided. The expansion of the WLAN Downlink Phase equals the reduction of the WLAN Uplink Phase because the total length of WiMAX frame is constant. Therefore, excessive expansion of the WLAN Downlink Phase reduces uplink traffic that needs for WiMAX UL Burst. This causes the degradation of uplink throughput. Finally, to prevent this throughput degradation, the minimum length of WLAN Uplink Phase is introduced. Accordingly, the beginning of WLAN Downlink Phase is rescheduled to match the end of the minimum length of WLAN Uplink Phase. Following this reasoning, the minimum length of WLAN Uplink Phase is decided so as to match the amount of WLAN uplink traffic and WiMAX uplink traffic as shown in Fig. 5.14. Hence, system throughput is improved by this scheduling scheme. Analysis details are presented in the Subsection 5.4.3. As a consequence, this scheduling change improves the throughput via the WLAN-WiMAX relay system.

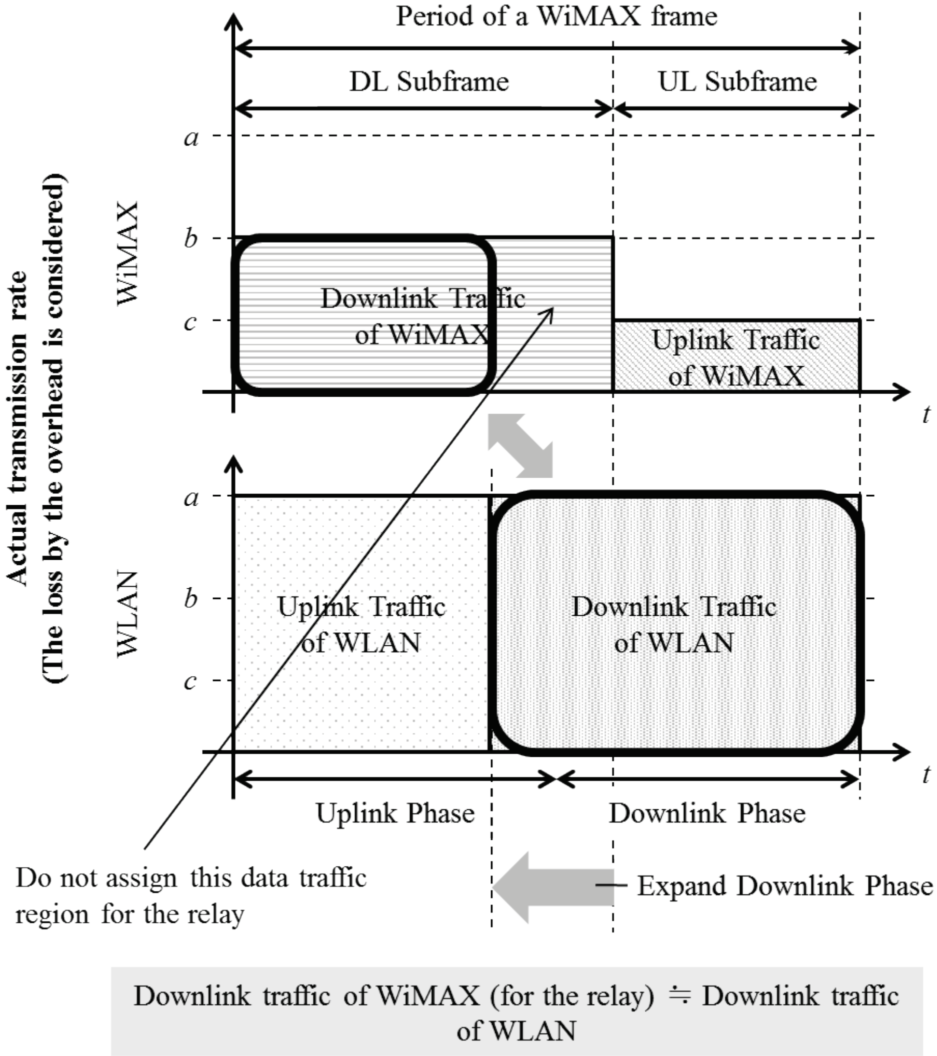

Fig. 5.13 The scheduling method for downlink.

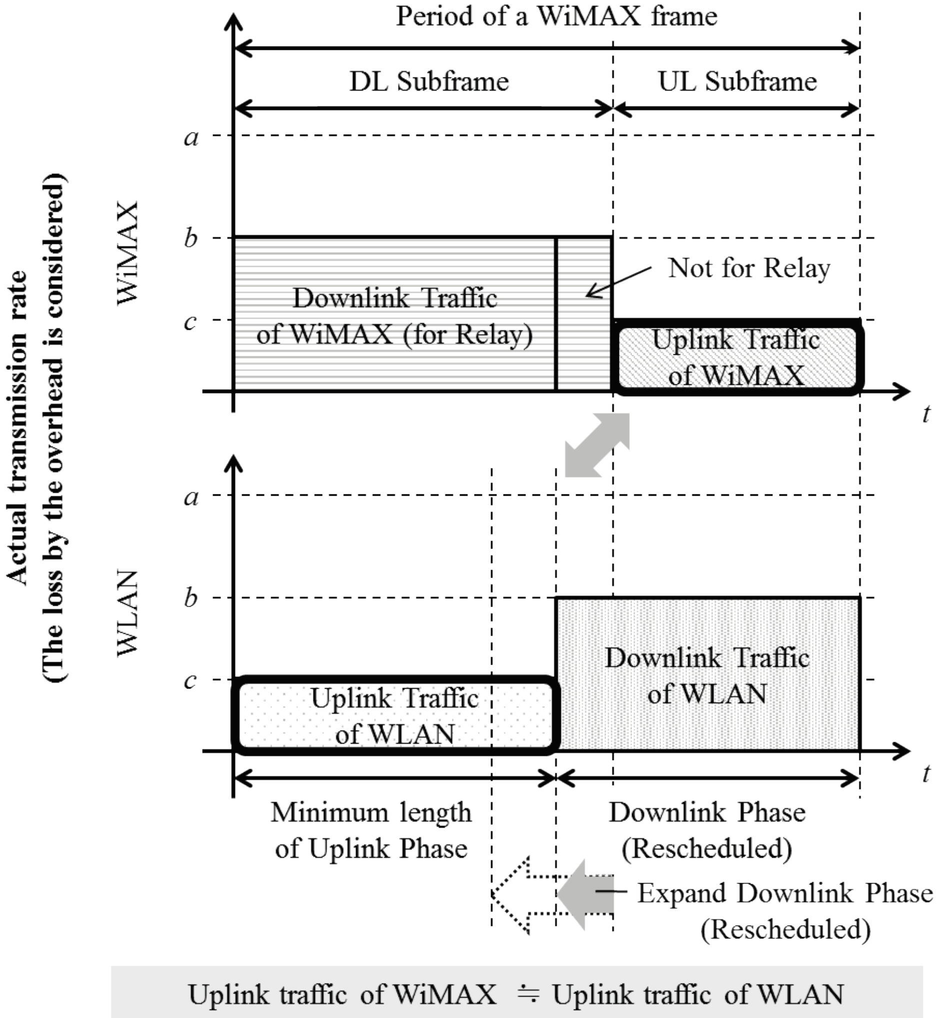

Fig. 5.14 The scheduling method for uplink.

5.4.3. Theoretical Calculation

In this subsection, details of the theoretical calculation used in Subsection 5.4.2 of the proposed scheme are explained here. Fig. 5.15 illustrates how to calculate for the optimal WLAN Downlink Phase.

Firstly, on the basic proposed scheme, the amount of traffic that received at WiMAX MS is defined as C_x in a WiMAX frame. As well, the amount of traffic that transmitted at WLAN AP is defined as C_w in a WiMAX frame. Then traffic difference C_{ex} shown as Eq. (5.1) will not be transferred to WLAN STAs.

$$C_{ex} = C_x - C_w . \tag{5.1}$$

In addition, the number of all subcarriers that WiMAX DL Burst uses is s, the number of OFDM symbols that DL Burst allocated to the wireless mobile router is L, and modulation bit number is m. Therefore, C_x is represented as follows,

$$C_x = s \times L \times m \times e . \tag{5.2}$$

Variable e is a coefficient of proportion of data payload in a DL Burst. It is assume that the allocation of DL Burst is to use all subchannels, and to arrange in the time direction for simplification. It is defined that the number of WLAN packets that can be transmitted in WLAN Downlink Phase is n_w. It is assumed that the Ethernet frame in 1500 bytes is payload of WLAN packet hereafter. Payload of the Ethernet frame that doesn't come up to 1500 bytes is assumed to be a_e as well. Therefore, C_w is represented as follows,

$$C_w = 1500 \times 8 \times n_w + a_e \times 8 . \tag{5.3}$$

Therefore, n_w is given as follows,

$$n_w = \mathrm{floor}\left[\frac{t_{DP} - T_O}{T_P}\right], \tag{5.4}$$

$$T_{O(a_e)} = T_{PSMP} + T_{ACK} + T_{PDU(a_e)} + T_{IFS} , \tag{5.5}$$

$$T_P = T_{PDU(1500)} + T_{IFS} . \tag{5.6}$$

The variables T_{DP} and T_{PDU} represent the length of the WLAN Downlink Phase before the scheduling and the length of a data frame (Protocol Data Unit: PDU), respectively. T_{PSMP}, T_{ACK}, and T_{IFS} represent each the length of a PSMP frame, an ACK, and IFS length.

Secondly, for the expanded scheduling scheme, the expanded length of WLAN Downlink Phase is defined as t_1. The period t_1 is led from the following calculations. It is assumed that the number of all OFDM symbols in DL Burst is L_{max}, and the length of an OFDM symbol is l. Therefore, the amount of traffic that WiMAX MS receives after the scheduling in a WiMAX DL Subframe is given by as C_x' shown below,

$$C_x' = C_x - \left\{ s \times \left[(L_{\max} - L) + \mathrm{ceil}\left(\frac{t_1}{l}\right) \right] \times m \times e \right\}. \tag{5.7}$$

The amount of traffic that WLAN AP transmits after the scheduling is given by C_w',

$$C_w' = (1500 \times n_w' + a_e') \times 8. \tag{5.8}$$

As well as before the scheduling, n_w' is the number of packets that have 1500 byte payload of Ethernet frames in WLAN Downlink Phase after the scheduling, and a_e' represents the payload of Ethernet frame whose size is less than 1500 bytes. Therefore, n_w' is given as follows,

$$n_w = \mathrm{floor}\left[\frac{(t_1 + t_{DP}) - T_O}{T_P}\right], \tag{5.9}$$

$$T_{O(a_e')} = T_{PSMP} + T_{ACK} + T_{PDU(a_e')} + T_{IFS}, \tag{5.10}$$

$$T_P = T_{PDU(1500)} + T_{IFS} \tag{5.11}$$

The scheduling scheme determines t_1 for which $C_x' = C_w'$. Therefore, t_1 is given by Eq. (5.12).

$$t_1 = \frac{s \times m \times e \times (2L - L_{\max}) - 1500 \times 8 \times \left(\frac{t_{DP} - T_{O(a_e')}}{T_p}\right)}{\frac{s \times m \times e}{l} + \frac{1500 \times 8}{T_p}}. \tag{5.12}$$

Finally, the final expanded length of WLAN Downlink Phase t_1' is decided. To calculate t_1', the minimum length of WLAN Uplink Phase t_2 is decided as follows. the amount of traffic that transmitted from WiMAX MS is defined as G_x in a WiMAX frame. The number of all subcarriers that WiMAX UL Burst uses is u, the number of OFDM symbols that UL Burst allocated to the wireless mobile router is J, and modulation bit number is y. Therefore, G_x is represented as follows,

$$G_x = u \times J \times y \times e. \tag{5.13}$$

Here, the quotient to divide G_x by 1500 bytes is assumed to n_u and the surplus is assumed to be p. Therefore, t_2 is represented as follows,

$$t_2 = T_P \times n_u + T_{R(p)}, \tag{5.14}$$

$$T_{R(p)} = T_{ACK} + T_{PDU(p)} + T_{IFS}. \tag{5.15}$$

It is assumed that t_{UP} represent the length of the WLAN Uplink Phase before the scheduling. Accordingly, the final expanded length of WLAN Downlink Phase t_1' is decided as follows,

$$t_1' = \begin{cases} t_{UP} - t_2 & (t_2 < t_{UP} - t_1) \\ t_1 & (t_2 \geq t_{UP} - t_1) \end{cases}. \tag{5.16}$$

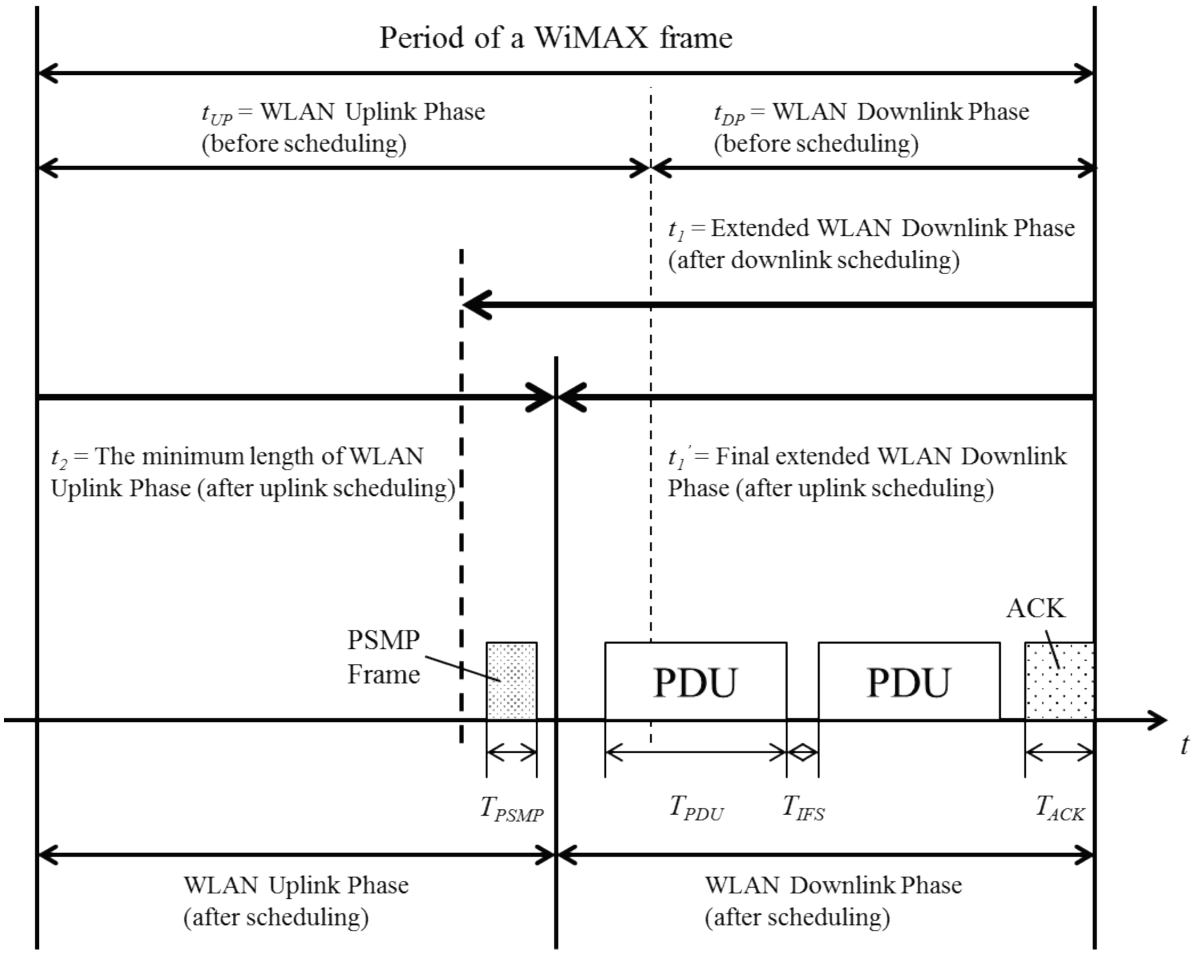

Fig. 5.15 Calculation for the optimal WLAN Downlink Phase.

5.5. Performance Evaluation

To clarify the performance of the proposed scheme, system throughputs of WiMAX BS and WLAN STA with the conventional and proposed schemes are evaluated by computer simulations. As the simulation conditions, It is assumed that if any packets (in the case of WLAN) or any OFDM symbols (in the case of WiMAX) suffer mutual system interference, those packets or symbols should be discarded. Moreover, it is assumed that there is no interference between the wireless mobile router and WiMAX BS or WLAN STA. These assumptions are reasonable given that the wireless mobile routers and WiMAX BS or WLAN STA will be very far apart compared to the distance between WLAN AP and WiMAX MS in the wireless mobile router. Moreover, downlink and uplink traffic flows occur simultaneously.

WLAN parameters of conventional schemes and of the proposed scheme comply with the IEEE 802.11g and the IEEE 802.11n legacy mode respectively. As well, WiMAX parameters comply with the IEEE 802.16e. Under this arrangement, the offered traffic (uplink and downlink) represents the traffic generated from the transmission edge. Fig. 5.16 shows the simulation model; the simulation parameters are given in Table 5.2.

The comparison of proposed and conventional schemes is performed under the above-mentioned conditions. Fig. 5.17 and Fig. 5.18 show the received downlink throughput characteristics of WLAN STA and the received uplink throughput characteristics of WiMAX. In Fig. 5.17, The ADC yields little throughput because most of data traffic are lost by the intermittent mutual system interference. The TDD limits the throughput to less than half the ideal value even though it prevents mutual system interference. In particular, uplink and downlink share the communication period already halved by time division done with WiMAX. Therefore, The TDD is able to obtain little throughput after the point of 11 Mbit/s in the offered traffic. On the other hand, the proposed scheme attained 1920% throughput from the ADC and 260% throughput from the TDD at the point of 17 Mbit/s in the offered traffic. Though the throughput characteristic of the proposed scheme is saturated after the point of 11 Mbit/s in the offered traffic, the reason is there is no room to expand WLAN Downlink Phase. In other words, optimal scheduling that WiMAX downlink traffic and WLAN downlink traffic is almost same has been achieved after that point.

In Fig. 5.18, the reason why little throughput has yielded in the ADC and the TDD is the same as the case of downlink. On the contrary, the proposed scheme obtained nearly ideal throughput. The proposed scheme obtains 1440% throughput from the ADC and twice from the TDD at the point of 10 Mbit/s in the offered traffic. Though the throughput characteristic of the proposed scheme and ideal is saturated after the point of 4 Mbit/s in the offered traffic, the reason is quite different from the uplink case. That is, because the boundary is up to 4 Mbit/s of WiMAX uplink throughput, it becomes impossible to exceed this value.

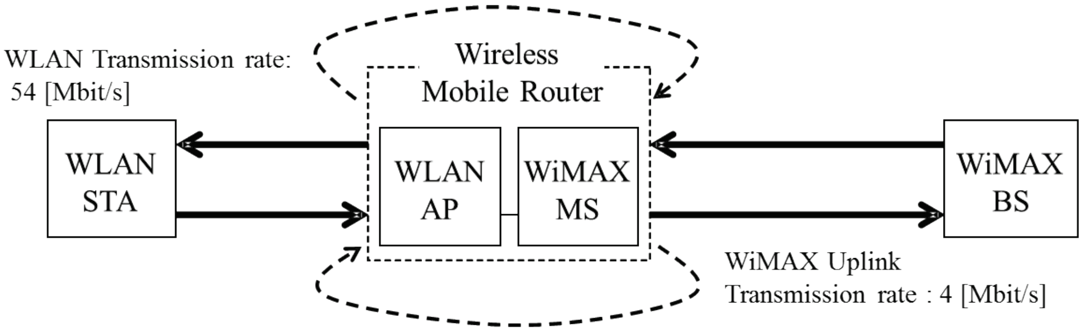

Fig. 5.16 Simulation model.

Table 5.2 Simulation parameters.

Evaluation Type	Downlink Evaluation		Uplink Evaluation	
Parameter	Downlink	Uplink	Downlink	Uplink
WLAN Offered Traffic Load [Mbit/s]	Through via WiMAX	30	Through via WiMAX	1-10
WiMAX Offered Traffic Load [Mbit/s]	3.7-18.7	Through via WLAN	18.7	Through via WLAN
Data Payload [byte]	1470		1470	
WLAN Transmission Rate [Mbit/s]	54	54	54	54
WiMAX Transmission Rate [Mbit/s]	3.7-18.7	4	18.7	4
IFS Parameters (WLAN only)	IEEE 802.11g		IEEE 802.11g	
DL/UL Ratio (WiMAX only)	32:15		32:15	
Scheduling Type (WiMAX only)	UGS		UGS	

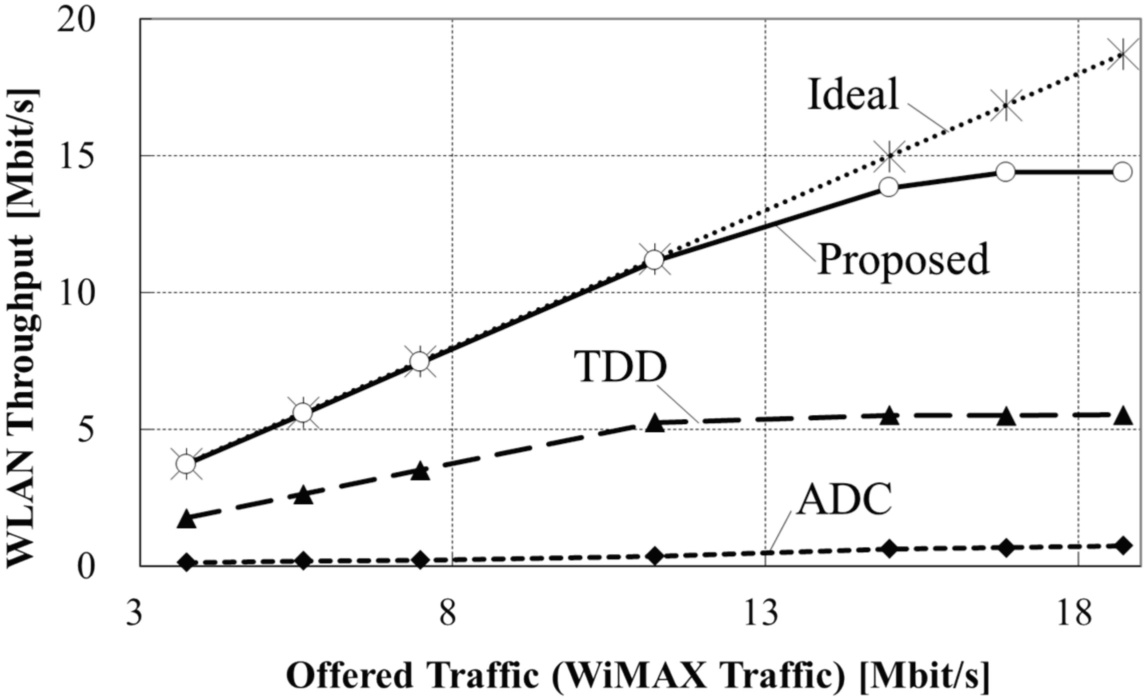

Fig. 5.17 Downlink relay throughput in the proposed and conventional schemes.

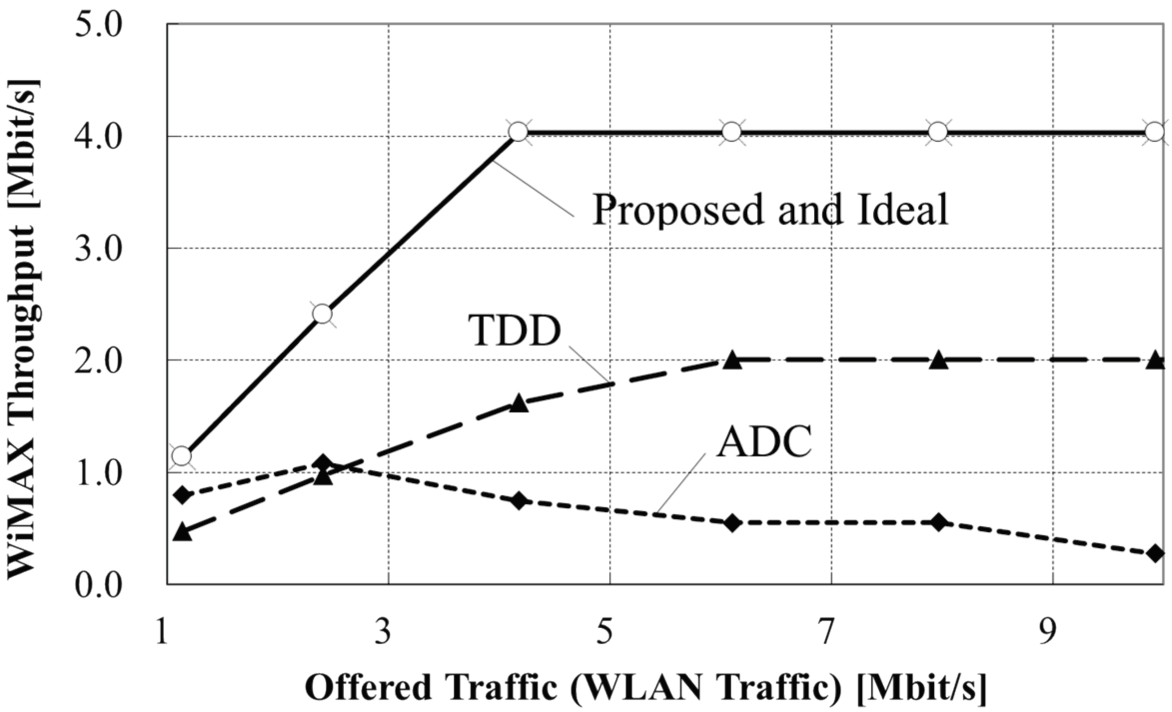

Fig. 5.18 Uplink relay throughput in the proposed and conventional schemes.

5.6. Summary

In this chapter, a novel mutual system interference avoidance technique on MAC protocol was proposed. The proposed scheme synchronizes the transmission and the reception timing of WiMAX and WLAN using the IEEE 802.11 PSMP and avoids mutual system interference. In addition to this proposition, the scheduling scheme to eliminate the gap of traffic that improves throughput characteristic via the WiMAX-WLAN relay system was proposed. Firstly, it was described that the impact of mutual system interference between WLAN and WiMAX units was clarified by the experiments. It was also showed that the conventional scheme of the ADC allows mutual system interference to significantly degrade throughput, and the addition of the TDD, while preventing mutual system interference, halves the throughput since it shares the communication period. On the other hand, the proposed scheme achieves good throughput; it eliminates mutual system interference by careful scheduling without wasting the communication period. The computer simulation confirmed its good performance. The proposed scheme succeeded in obtaining about 2000% throughput compared with the ADC and about 300% throughput compared with the TDD.

In this chapter, the scenario of one wireless mobile router connected to WiMAX BS was discussed as an initial investigation. As future work, I must extend the scheduling algorithm to improve throughput performance when multiple wireless mobile routers are connected to WiMAX BS; of the goal is to ensure that the optimal WiMAX DL Burst allocation is achieved. I note that the time position of DL Burst for each wireless mobile router in WiMAX frame may limit the length of WLAN Downlink phase, and this limitation might degrade system performance. Even without this extended algorithm, the proposed scheme ensures that mutual system interference problem is suppressed. That is, the basic concept of the proposed scheme, which is to make the PSMP sequence as long as the WiMAX frame, is effective.

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Chapter 6

Conclusions

6. Conclusions

This dissertation has presented research results on WLAN systems regarding techniques of improvement on communication quality in wireless dense environments by reducing heavy collisions, of construction of user level quality of service classes by introducing two types of fixed back-off, of coexistence with other mobile communication systems by avoiding mutual system interference.

The environment for utilization of WLAN systems changes significantly over the last decade. Although terminals that use WLAN systems in the early stages were almost PC and WLAN systems were only replacements for wired LAN systems, nowadays many mobile devices such as smartphones, tablet PCs, mobile routers, gaming machines, and sensor devices, utilize WLAN systems and WLAN systems become important access networks. Moreover, traffic offloading of heavy traffic from mobile communication systems to WLAN systems is aggressively utilized. However, these changes of WLAN systems resulted in the increase of congested situations with many WLAN STAs, i.e., wireless dense environments. In the wireless dense environment, shortage of bandwidth resource needed for sufficient communication quality is caused by mechanism of contention based MAC protocol of WLAN systems. Sophistication of WLAN systems have been progressed in the IEEE 802.11 standard association. A lot of the standards regarding WLAN systems were published to improve transmission rates and to enhance various function for convenience. However, the fundamental MAC protocol of WLAN systems is nearly unchanged due to maintaining interoperability. This conventional design of MAC protocol of WLAN systems cannot cope with issues raised in the wireless dense environments. Specifically, it is integral to enhance communication quality that following three issues are solved in wireless dense environments.

1) Generation of co-channel interference between STAs because of frame collisions that are caused by simultaneous transmissions: In the CSMA/CA, each STA selects random offset timeslot before transmission and this random offset timeslot make difference of the timing for transmission among the STAs. However, the range of the number of timeslot is limited within small number because the conventional WLAN systems do not assume wireless dense environments. Therefore, the probability of frame collision increases in proportion to the number of STAs.

2) Establishing QoS control architecture for each user level priority control: In the CSMA/CA, an AP does not designate transmission timing for each STA. This operation does not ensure the priority control for each user. In other words, the priority for all STAs is impartial. Besides, the EDCA provides a QoS mechanism for WLAN systems. However, the EDCA prioritizes each traffic flow based on categorized applications and not based on specific STAs. Therefore, no user level priority control is constructed in the existing WLAN systems.

3) Inter-system interference caused by other wireless systems: In WLAN systems, an AP does not provide any mechanism for protection against the mutual system interference between systems which utilize the ISM bands on MAC protocol. Specifically, in a wireless mobile router that has the functions of WLAN AP and of WiMAX MS, the emission of the spectrum mask leaks outside the band and caused mutual system interference when the frequency band of WLAN and WiMAX is adjacent. This is because the space between each interface is very close due to small chassis of the wireless mobile router.

In this dissertation, in order to solve these issues, the following techniques have been proposed.

1) A simple and adaptive frame collision control scheme that can mitigate severity of contention for obtaining channel access in order to reduce heavy collisions between STAs.

2) A pseudo-centralized control technique that enables control of flexible bandwidth allocation to each specific STA in order to establish a control mechanism of user level priority for WLAN systems.

3) A scheduling technique that controls timing of transmission for WLAN systems in order to avoid mutual system interference between WLAN and WiMAX systems.

The following summarizes the results obtained through this research.

In Chapter 3, to reduce heavy collisions between STAs that cause co-channel interference in wireless dense environments, a simple scheme that decreases the number of frame collisions by refraining from transmission during the certain period defined as the Post-IFS after a successful transmission was proposed. In the proposed scheme, a STA sends a data frame if the wireless channel is idle when the time for waiting for back-off time has expired. If an AP receives the data frame successfully, the AP returns an ACK frame to the STA. This operation is the same as the conventional CSMA/CA. If the STA receives an ACK frame, the STA refrains from transmitting any data frames during Post-IFS whether or not the STA has consecutive frames to send in its transmission queue. This is a unique operation and it can lessen the number of other competing STAs. This results in reduction in the frame collision probability. The proposed scheme is easy to implement into existing WLAN devices because no original frames need to be defined and it has only a slight impact on the existing CSMA/CA protocol. The proposed scheme improves the system performance including the throughput characteristics, access delay and the number of retransmissions by reducing the number of collisions. The length of the Post-IFS is a key factor in improving the system performance for the proposed scheme. If the AP can estimate the optimal value of the Post-IFS, collision-free operation similar to that in non-contention based protocol is performed. Even if the optimal Post-IFS is not estimated, the number of competing STAs and the collision probability are decreased. Two estimation methods were also introduced: one was fixed estimation that specifies the value of the Post-IFS using the distribution of observed frames, and the other was adaptive estimation that was based on the fixed estimation and utilizes the idea of the steepest descent method to explore the optimal value for the Post-IFS. The effects of the proposed scheme were verified based on computer simulations and experiments. The proposed scheme is effective in particular in a wireless dense environment under both saturated and non-saturated conditions. The results of the computer simulations showed that the proposed scheme achieves up to 40% higher system throughput compared to the case in which the proposed scheme is not introduced.

In Chapter 4, to establish a control mechanism of user level priority for WLAN systems, a pseudo-centralized control scheme based on the CSMA/CA was proposed. The proposed scheme suppresses collisions between proposed STAs, improves the throughput characteristics and shortens the access delay. Moreover, the proposed scheme controls the user-oriented QoS by setting two kinds of fixed back-off values, namely, the IBV and CBV. The AP specifies the IBV and assigns it as the back-off value when the first transmission of each STA occurs. The IBV is a unique and non-zero value that is different for each STA. During the first transmission occurs, there is no collision between the proposed STAs due to the different back-off values decided by the IBV. Afterwards, the CBV is assigned as the back-off value for each successive transmission unless a collision occurs. The CBV is also a fixed value and is specified by the AP. However, the value is common to all proposed STAs. Therefore, the IBV establishes different offset times for each STA, while the CBV sustains the relation of the offset in a cyclic manner. This operation avoids collisions between the proposed STAs and improves the system throughput. If a low number is assigned to the IBV, the priority of the proposed STA increases, and vice versa. Conversely, increasing the CBV increases the priority level of the DCF STAs. In addition, the granularity of the user-oriented QoS classes can be specified by setting the appropriate IBVs. Moreover, the conventional DCF STAs can execute their transmissions as usual during the pseudo-centralized control of the proposed scheme, unlike existing non-contention based control schemes. These effects were verified through computer simulations. The proposed scheme is highly effective in protecting the user-oriented QoS in wireless dense environments. The results of computer simulations showed that the proposed scheme can achieve up to over 300% higher user throughput, compared to the case in which the proposed scheme is not introduced under the coexistence environment with DCF STAs. In addition, all the proposed STAs achieved 70% higher throughput than the DCF STAs under a non-coexistence environment. Moreover, the proposed scheme can be improved to enable control of not only user-oriented QoS but also application-oriented QoS by developing the queuing mechanism.

In Chapter 5, to avoid mutual system interference between WLAN and WiMAX systems, a scheduling scheme that controls timing of transmission for WLAN systems was proposed. The proposed scheme synchronizes the transmission and the reception timing of WiMAX and WLAN using the IEEE 802.11 PSMP and avoids mutual system interference. The proposed scheme makes the PSMP sequence as long as a WiMAX frame. That is, the proposed scheme makes the length of WLAN Uplink Phase equal to the length of WiMAX DL Subframe. The length of WLAN Downlink Phase is made equal to the length of WiMAX UL Subframe as well. Accordingly, the proposed scheme enables the wireless mobile router to transmit signals only in WLAN Downlink Phase, and to receive signals only in WLAN Uplink Phase. That is, the wireless mobile router eliminates mutual system interference which realizes highly effective relay transmission. Although WLAN STAs or APs cannot execute only transmission or reception in a certain period due to the handshake mechanism of an ACK frame in the DCF, the PSMP function enables that mechanism by indicating the transmission timing for each STA. In addition to this proposition, the scheduling scheme to eliminate the gap of traffic that improves throughput characteristic via the WiMAX-WLAN relay system was proposed. Moreover, it was described that the impact of mutual system interference between WLAN and WiMAX units was clarified by the experiments. It was also showed that the conventional scheme of the ADC allows mutual system interference to significantly degrade throughput, and the addition of the TDD, while preventing mutual system interference, halves the throughput since it shares the communication period. On the other hand, the proposed scheme achieved good throughput; it eliminates mutual system interference by careful scheduling without wasting the communication period. The computer simulation confirmed its good performance. The proposed scheme succeeded in obtaining about 2000% throughput compared with the ADC and about 300% throughput compared with the TDD.

As mentioned above, this dissertation proposed techniques that achieve significant enhancement of the performance of WLAN systems by introducing practical media access control schemes. The results should contribute to overcome ongoing and forthcoming difficulties in wireless dense environments. Finally, it is my sincere hope that this dissertation will aid in actualizing future WLAN systems.

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List of Publications

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[1] A. Kishida, M. Iwabuchi, T. Shintaku, T Onizawa and T. Sakata, "Frame Collision Reduction Method Employing Adaptive Transmission Control for IEEE802.11 Wireless LAN System," IEICE Transactions on Communications, Vol.E97-B, No.9, pp.1790-1799, September 2014.

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